Theory Lessons from the early LHC runs at O(1 TeV)

Peter Skands (CERN PH-TH)

CMS Physics Week, CERN, March 18, 2010

Disclaimer

*"**It is a** huge mistake to theorize before one has data - One tends to twist fact to suit theory, instead of theory to suit fact"*

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Sherlock Holmes (2009)

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- ***Focus* on important** outstanding questions *addressed by early LHC data*

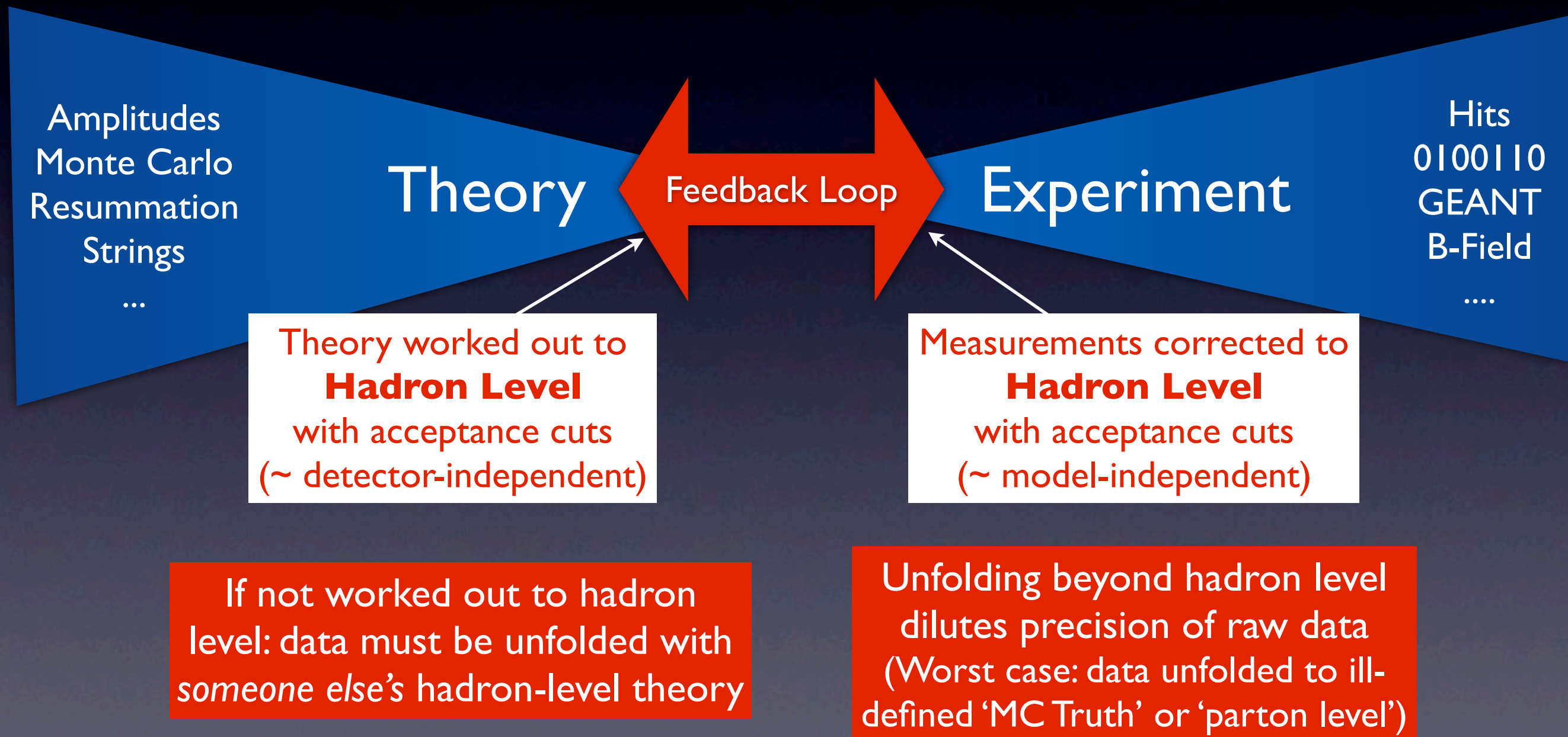- **The answers are** crucial to *improving* our physics models

Monte Carlos and Precision

- **A Good Physics** Model gives you

  - **Reliable calibrations** for both signal and background (e.g., jet energy scales)

  - **Reliable corrections** (e.g., track finding efficiencies)

  - **Background estimates** with as small uncertainty as possible (fct of both theoretical accuracy and available experimental constraints)

  - **Reliable discriminators** with maximal sensitivity to New Physics

Count what is Countable
Measure what is Measurable
(and keep working on the beam) G. Galilei

Amplitudes
Monte Carlo
Resummation
Strings

....

Theory

Feedback Loop

Experiment

Hits
0100110
GEANT
B-Field

....

Theory worked out to
Hadron Level
with acceptance cuts
(~ detector-independent)

Measurements corrected to
Hadron Level
with acceptance cuts
(~ model-independent)

If not worked out to hadron level: data must be unfolded with *someone else's* hadron-level theory

Unfolding beyond hadron level dilutes precision of raw data
(Worst case: data unfolded to ill-defined 'MC Truth' or 'parton level')

Monte Carlo Truth

- **Example:** Drell-Yan p_T distribution.

  - **Measured: final-state** leptons (+ photons)

  - **QED is "known"** - use MC/model to correct back to "True Z boson"

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The "Q" in QED

- "MC Truth" **is:** useful indicator of dominant path.
  Equivalent to Young knowing which slit the photon passed through!

In Quantum Mechanics

- **Photons emitted off** other particles *interfere* with those from Z decay - *no unique FSR correction*

- **Leptons from Z decay** may interfere with other leptons in event - *no unique lepton assignment*

- "MC Truth" **is not:** quantum mechanically meaningful

See also Hesketh et al., in arXiv:1003.1643

A Proposal

- **While it is** <u>essential</u> to provide the data in terms of observables, it may still be <u>desirable</u> to derive further theoretical corrections for comparisons ...

- We recommend such correction factors be provided in a table, rather than being applied to the data.

- Using this table, (the inverse of) such corrections could also be applied to allow direct comparisons of cruder models to the data while maintaining the separation of measurement and theory

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Phase Space Extrapolations

Measure what is Measurable

- Example for discussion. What would be lost by the following modification?

The $dN_{ch}/d\eta$ spectrum was obtained by summing the measured differential yields for $0.1 < p_T < 3.5$ GeV/c and adding the result to the integral of the fit function for $p_T < 0.1$ GeV/c and $p_T > 3.5$ GeV/c. The latter term amounts to 5% of the total.

CMS-QCD-09-010 [arXiv:1002.0621]

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Table X contains , i.e., our estimate of the additional correction that would be necessary to compare to an all-phase-space calculation or measurement, with a correspondingly larger uncertainty generated by the errors in Table X.

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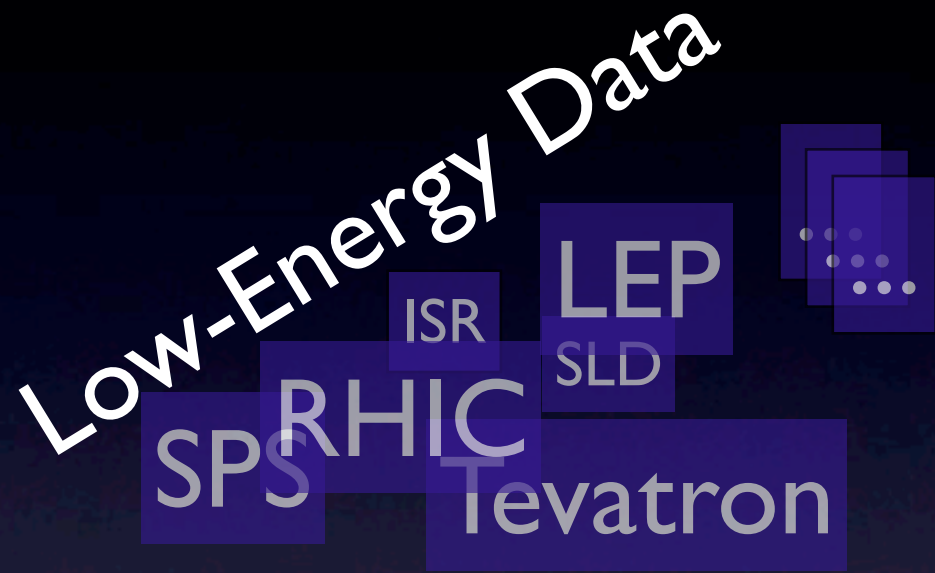
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Constraining Models
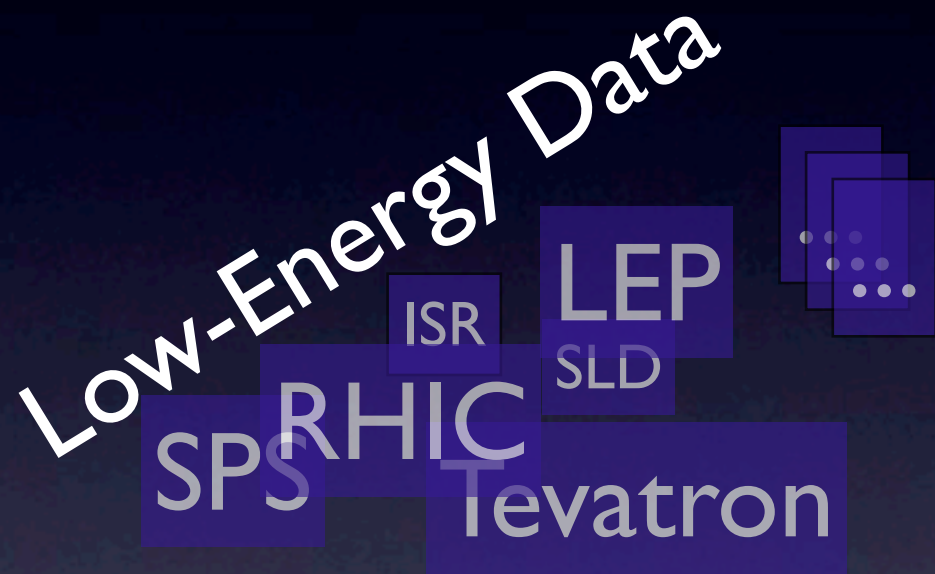
Low-Energy Data

ISR

LEP

SLD

SPS

RHIC

Tevatron

- A wealth of data available at lower energies

- Used for constraining ('tuning') theoretical models (E.g., Monte Carlo Event Generators)

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- Which model would you trust more? One that also describes SPS, RHIC, Tevatron, Low-Energy LHC? Or one that doesn't?

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But wait ... which gaps?

Charged Multiplicity

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  - **Experimental Complications: Corrections** for Trigger Bias, Diffraction, Zero Bin, Long-Lived particles & secondaries, charged *particles* vs charged *hadrons*, QED effects, extrapolations from raw measurement to: hadron-level (with acceptance cuts) and/or to: hadron-level (full phase space), ...
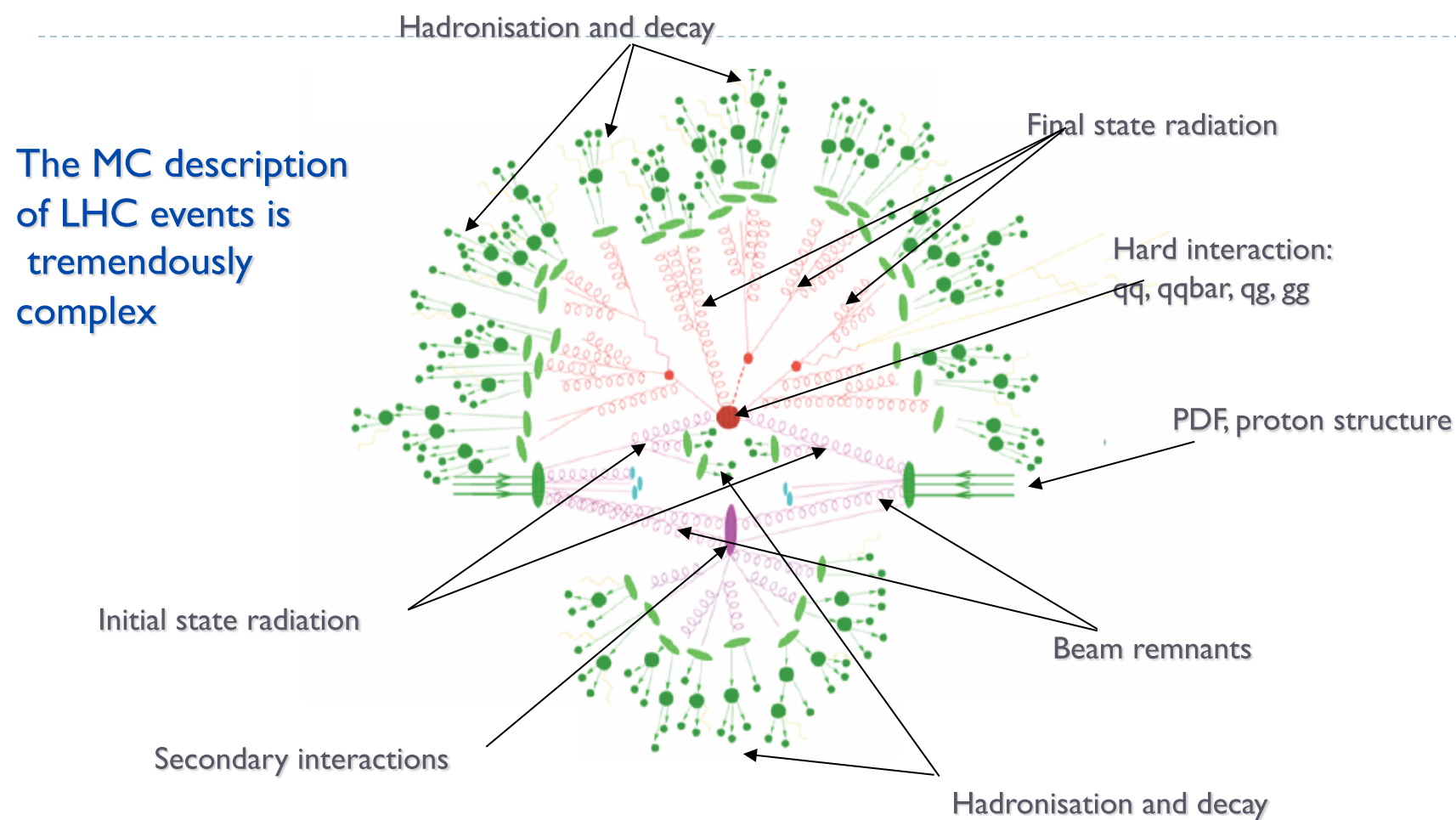
Charged Multiplicity

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  - **Theoretical Complications:**

    - N_{ch} is very **IR sensitive** ... A model that fits N_{ch} but fails on p_T is getting the overall energy flow wrong - more fundamental?

Charged Multiplicity

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  - **Theoretical Complications:**

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  - Need to test several distributions, in several phase space regions, to get complete picture

    - Who breaks down and where : can see patterns and ask why

    - *(Note: a 10% agreement with an IR sensitive number is pretty good...)*
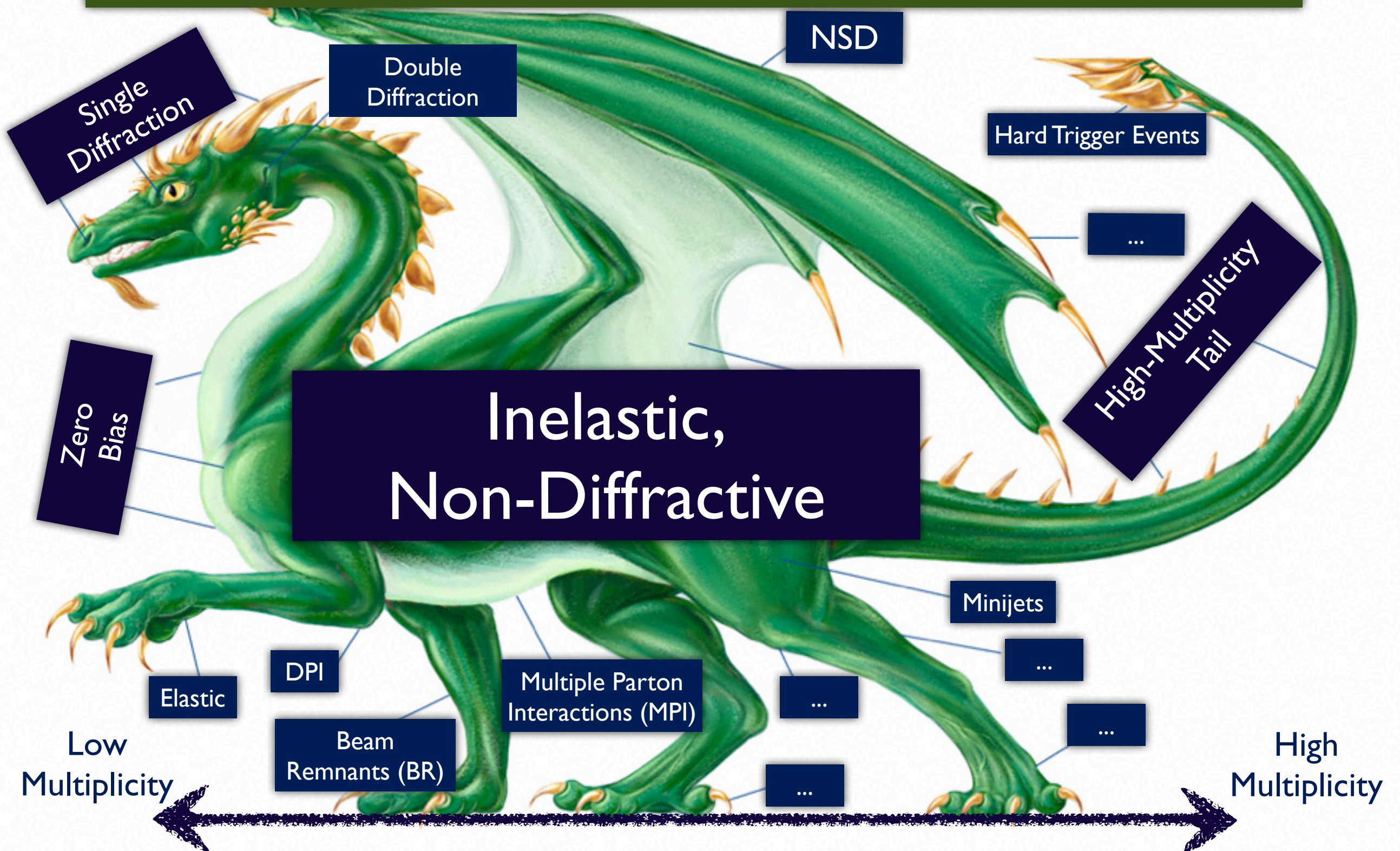
Dissecting Minimum-Bias

Physics requirements: basics

The MC description
of LHC events is
 tremendously
complex

Hadronisation and decay

Final state radiation

Hard interaction:
qq, qqbar, qg, gg

PDF, proton structure

Initial state radiation

Beam remnants

Secondary interactions

Hadronisation and decay

 This is a schematization to be able to cut down the problem in pieces and
 model them in a different way. The "pieces" are correlated !

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7th MCNet Workshop   14/1/2010

(slide from F. Cossutti (CMS), 7th MCnet Annual Meeting, January 2010)

Dissecting Minimum-Bias

NSD

Single Diffraction

Double Diffraction

Hard Trigger Events

...

High-Multiplicity Tail

Zero Bias

Inelastic, Non-Diffractive

Minijets

...

DPI

Elastic

Multiple Parton Interactions (MPI)

...

...

Beam Remnants (BR)

...

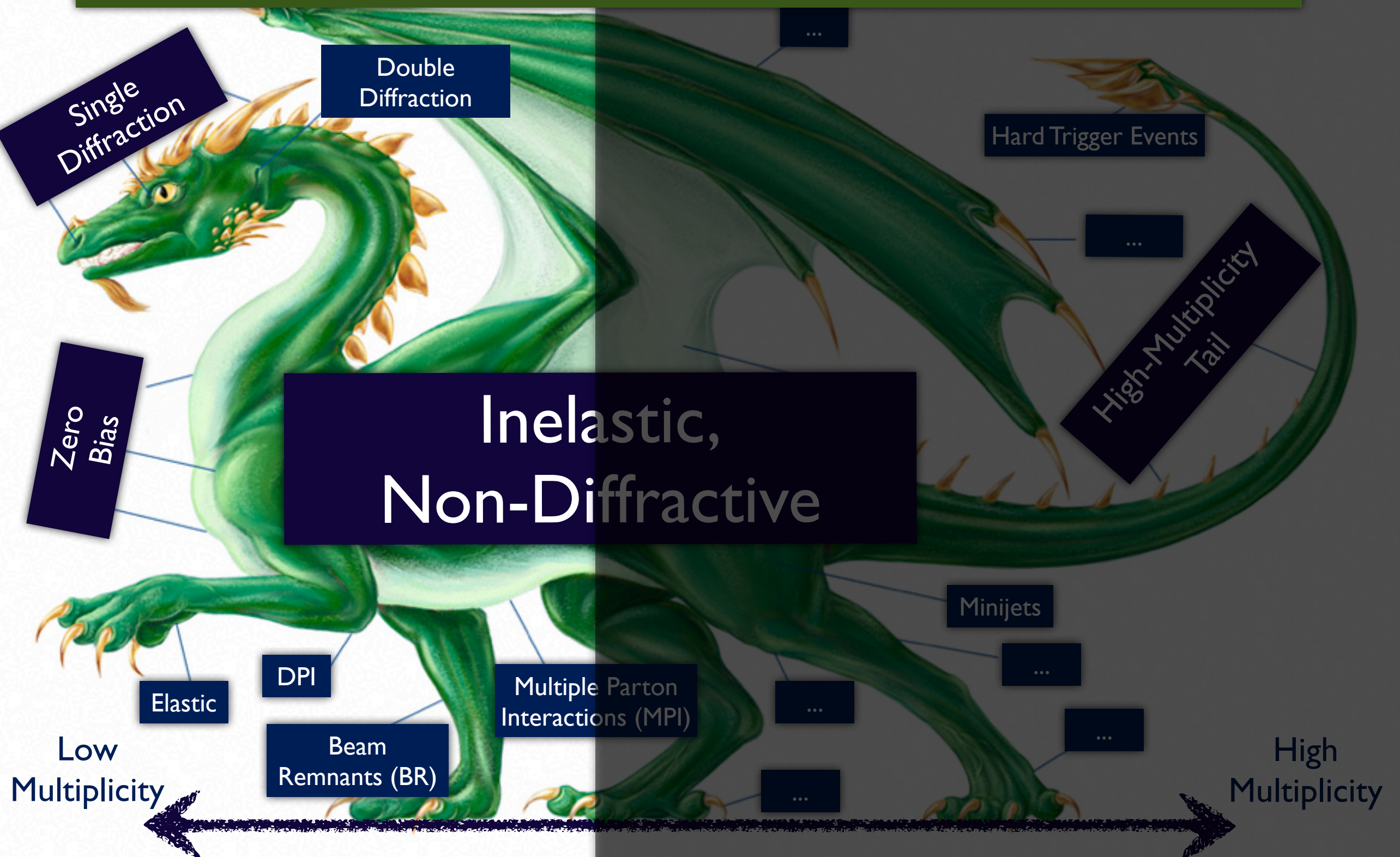Low Multiplicity

High Multiplicity

Measured Results

- ## How to Compare to Older Measurements?

  - Bubble chambers etc extrapolated to full phase space
  - More model-dependent at Tevatron and LHC experiments

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- ## How to Compare to Theory?

  - Inelastic > 'NSD' > Inelastic Non-Diffractive, ... ?

    - For all: Define <u>event set in terms of hadron-level cuts</u> (model-*inspired, yes,* but not model-*dependent*)

  - Model constraints not helped by filling up unmeasured region with some model/fit (especially if it is some other guy's model) - Keep main measured result as close to raw acceptance as possible. Extrapolate *only* to do comparisons (inflates uncertainties)

Issues at Low Multiplicity

Single Diffraction

Double Diffraction

Hard Trigger Events

...

High-Multiplicity Tail

Zero Bias

Inelastic, Non-Diffractive

Minijets

...

DPI

Elastic

Multiple Parton Interactions (MPI)

...

...

Beam Remnants (BR)

...

Low Multiplicity

High Multiplicity

Low Multiplicities: Correcting for Diffraction

- Diffractive processes

  - Large part of total cross section

  - Populate the low-multiplicity bins: lower $<N_{ch}>$

  - Characteristic rapidity spectrum with large rapidity gaps: affect $dN_{ch}/d\eta$

  - Impossible to interpret min-bias spectra without knowing precisely how diffraction was treated
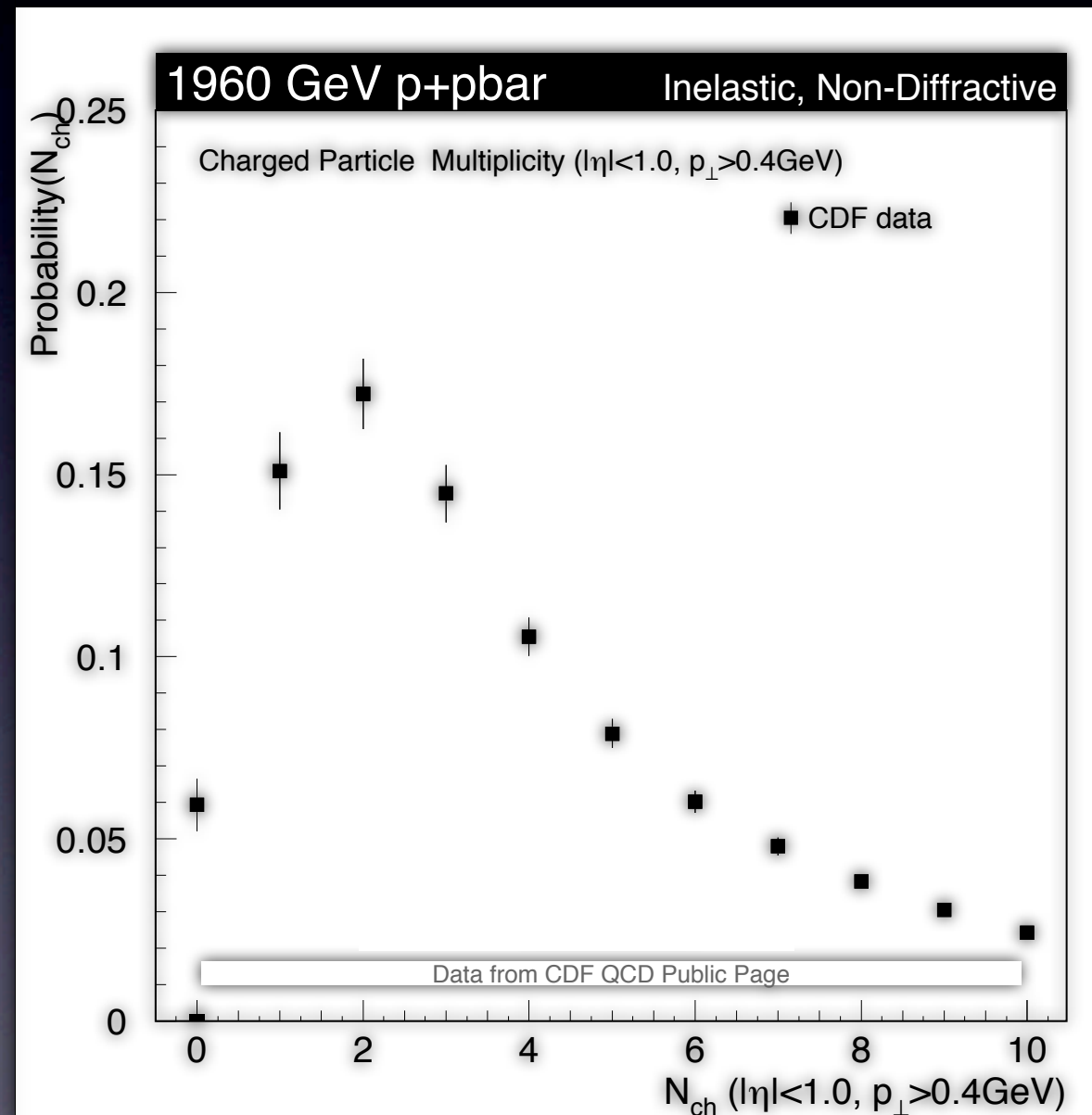
Low Multiplicities: Correcting for Diffraction

- ## CDF Run-I Data

  - Corrected to pT>0.4 GeV instead of full PS: less model dependence

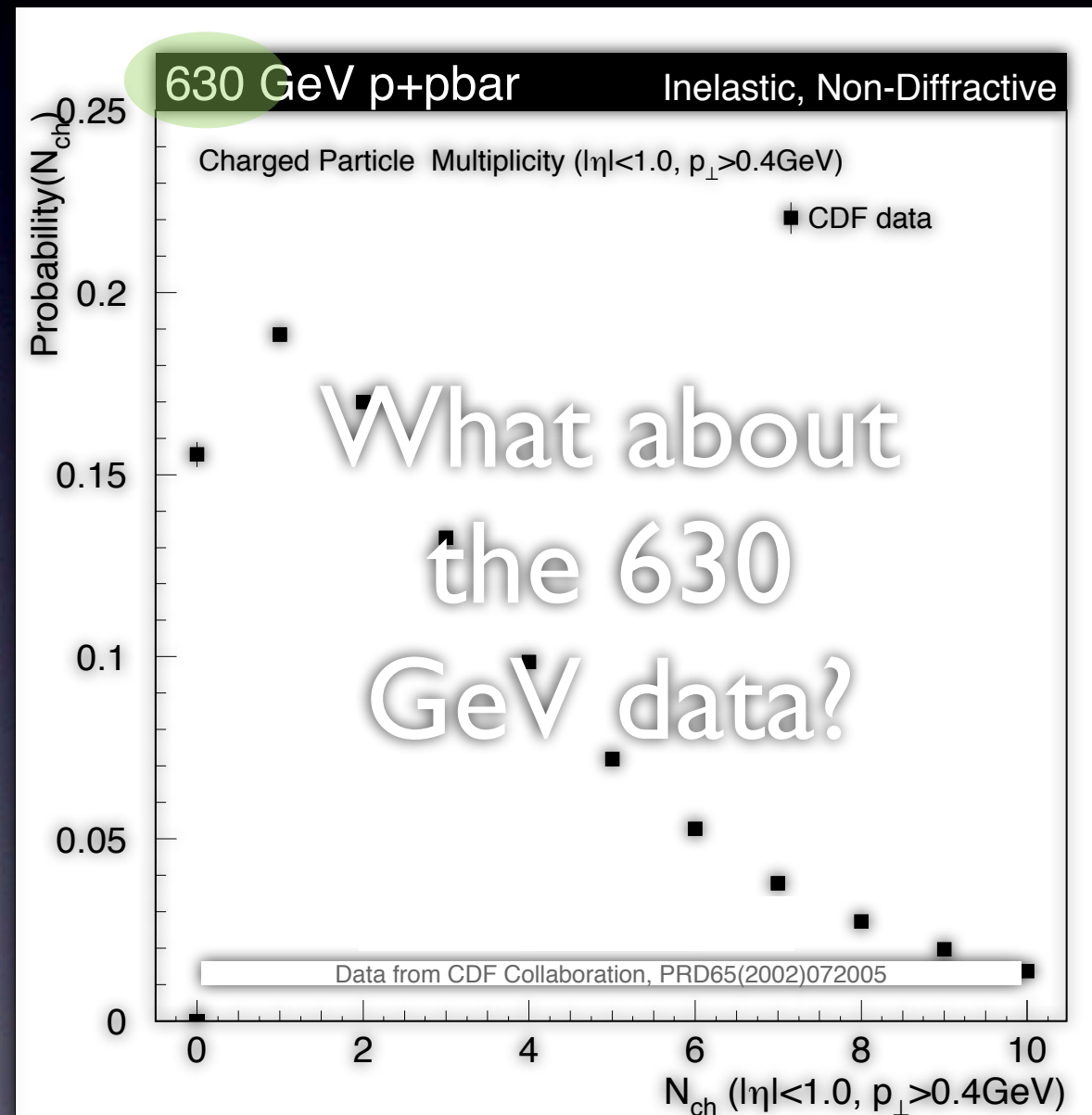 - First few bins corrected for diffraction (also affects average Nch and dN/deta)
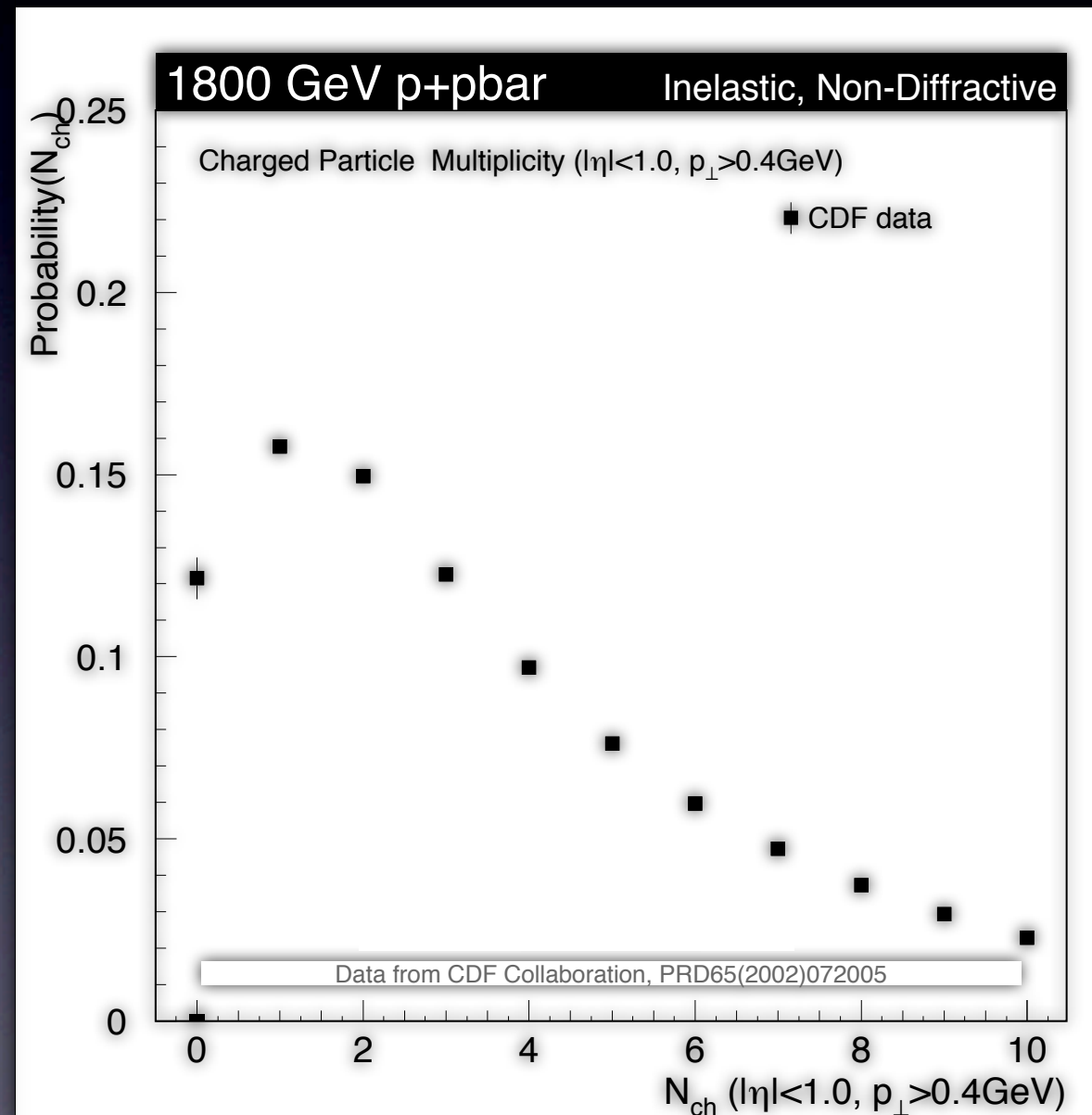
Low Multiplicities: Correring for Diffraction

- CDF Run-II Data

  - Corrected to pT>0.4 GeV instead of full PS: less model dependence

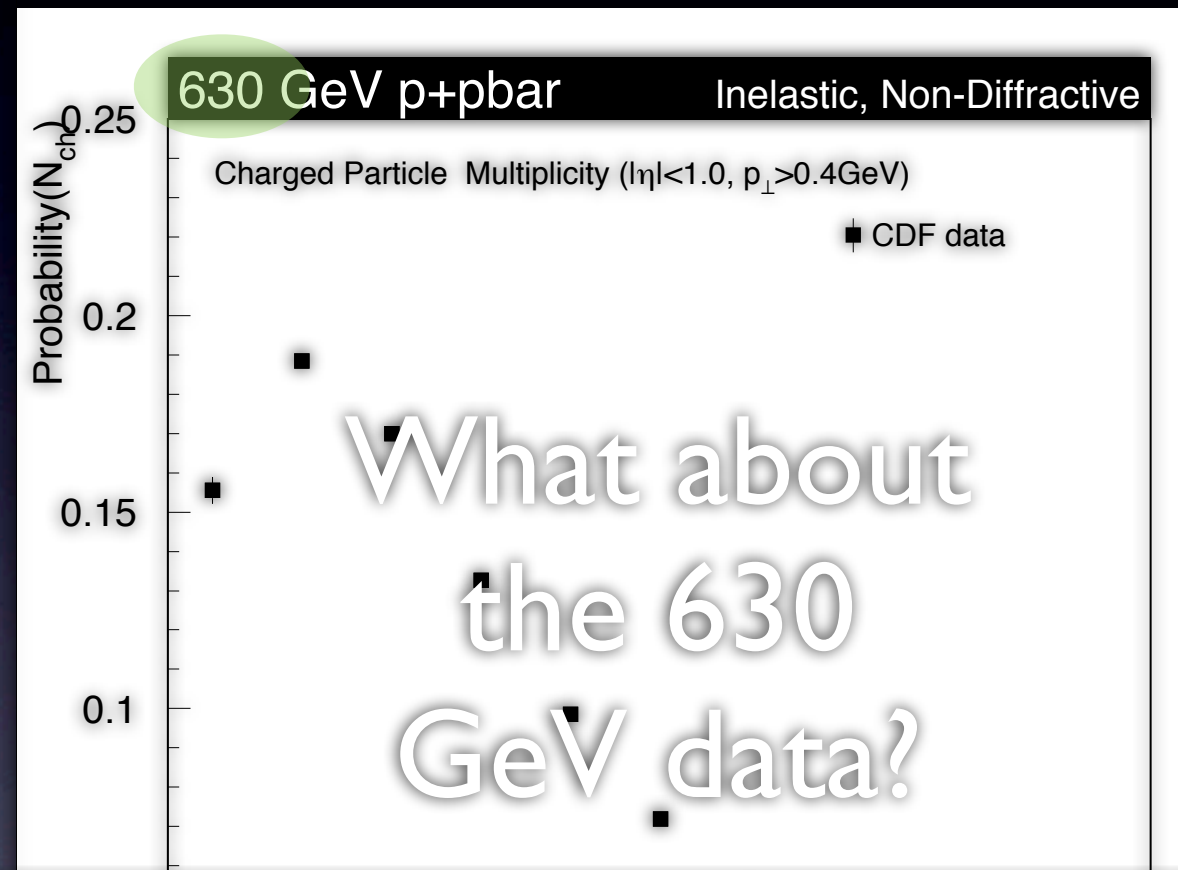 - First few bins corrected for diffraction (also affects average Nch and dN/deta)

Low Multiplicities: Correcting for Diffraction

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630 GeV p+pbar   Inelastic, Non-Diffractive

Charged Particle Multiplicity ($|\eta|<1.0$, $p_\perp>0.4$GeV)

Probability(N_{ch})

■ CDF data

What about the 630 GeV data?

Data from CDF Collaboration, PRD65(2002)072005

N_{ch} ($|\eta|<1.0$, $p_\perp>0.4$GeV)

Low Multiplicities: Correcting for Diffraction

- CDF Run-1 Data

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  - First few bins

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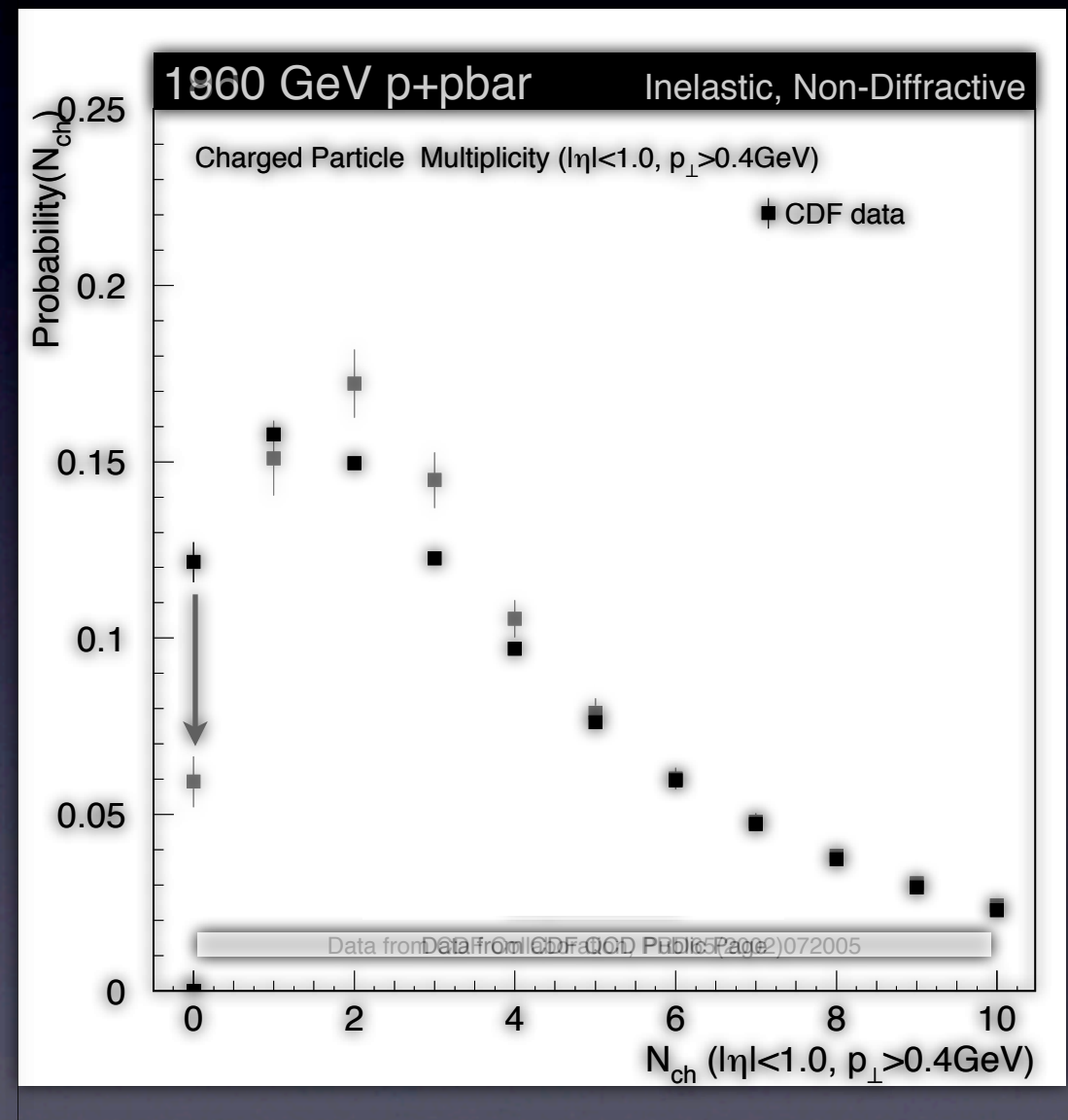
CDF data

What about the 630 GeV data?

LHC Measurements at 900 and 2360 GeV, with a well-defined, agreed-upon, definition of diffraction can kill this issue

The Zero Bin

- The most problematic is the zero bin: *the event was triggered, but no fiducial tracks*

  - *E.g, was it a diffractive event with no tracks, or an inelastic non-diffractive event, with no tracks? Or ...?*

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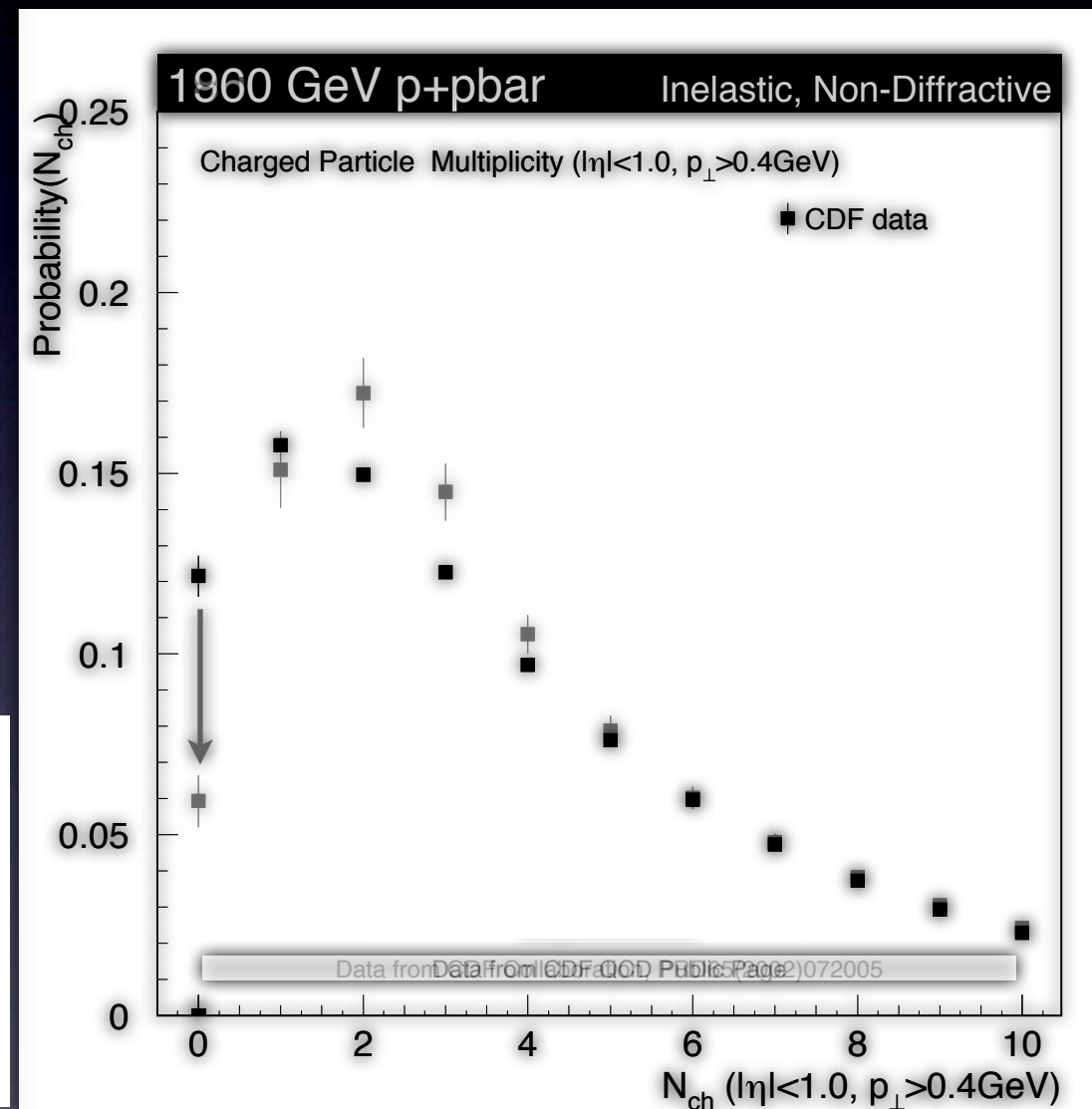
	$\dfrac{\langle N_{\mathrm{ch}}\rangle\,|_{N_{\mathrm{ch}}\geq 0}}{\Delta\eta\Delta\phi}$	$\dfrac{\langle N_{\mathrm{ch}}\rangle\,|_{N_{\mathrm{ch}}\geq 1}}{\Delta\eta\Delta\phi}$	$\dfrac{\langle N_{\mathrm{ch}}\rangle\,|_{N_{\mathrm{ch}}\geq 2}}{\Delta\eta\Delta\phi}$	$\dfrac{\langle N_{\mathrm{ch}}\rangle\,|_{N_{\mathrm{ch}}\geq 3}}{\Delta\eta\Delta\phi}$
LHC 10 TeV	0.40 ± 0.05	0.41 ± 0.05	0.43 ± 0.05	0.46 ± 0.06
LHC 14 TeV	0.44 ± 0.05	0.45 ± 0.06	0.47 ± 0.06	0.51 ± 0.06

Predictions for Mean Densities of Charged Tracks

PS, Perugia Proceedings, arXiv:0905.3418 [hep-ph]

Redefine the event sample to include at least one fiducial track?

Ways Out

A) Trust the theorists. Correct to specific set of fundamental processes ➡ NSD, INEL, ...

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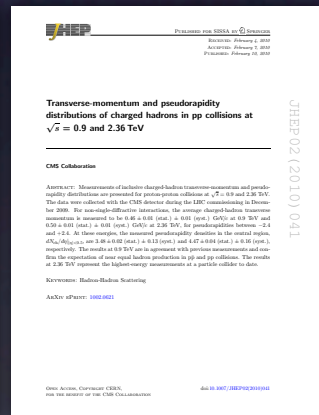
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ALICE Collaboration, Eur. Phys. J. C65 (2010) 111
CMS Collaboration, JHEP 02 (2010) 041

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However, it lacks a clear definition at the particle level

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```
 I  particle/jet  P(I,1)       P(I,2)       P(I,3)       P(I,4)       P(I,5)
 1  p+            0.38955     -0.09031    -444.18188    444.18305     0.93827          eta gap
 2  p+            0.55491     -0.32947     118.14484    118.15033     0.93827       = 13.6 units
 3  pi+          -0.10520      0.04623      21.97324     21.97398     0.13957
 4  pi-          -0.36420      0.20220      79.60000     79.60121     0.13957
 5  pi+           0.18465     -0.31136      44.33333     44.33503     0.13957
 6  pi-          -0.65347      0.35445      10.76828     10.79481     0.13957
 7  pi+          -0.31719     -0.18864       4.89293      4.90881     0.13957
 8  pi-           0.18684     -0.24438       0.75472      0.82687     0.13957
 9  pi+           0.01778      0.47298       1.28424      1.37578     0.13957
10  pi-           0.28540     -0.36795       2.98245      3.02181     0.13957
11  K+            0.01880      0.15742       2.95334      2.99849     0.49360
12  pi-           0.07232      0.23225       6.16625      6.17263     0.13957
13  pi+          -0.37412      0.04117       0.68340      0.79257     0.13957
14  pi-           0.12547      0.33701       2.03239      2.06867     0.13957
15  pi+           0.03865      0.05823       0.98258      0.99490     0.13957
16  pi-           0.16134      0.03535       4.09086      4.09657     0.13957
17  pi-          -0.06906      0.08845       1.96279      1.97095     0.13957
18  pi+           0.11852     -0.32616       3.70555      3.72438     0.13957
sum(p). mass:     0.27097      0.16745    -136.87069    751.99084   739.42987
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eta gap
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MC "Truth" : Double Diffractive

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14	pi-						
15	pi+						
16	pi-						
17	pi-						
18	pi+						
sum(p). ma							

MC "Truth" : Double Diffractive

Minimal Conclusion: gap definition not foolproof if we see charged only

I	particle/jet	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	p+	0.18101	-0.23124	427.60408	427.60521	0.93827
2	p+	-0.06244	-0.10079	-231.29111	231.29304	0.93827
3	K+	0.33646	0.18878	-33.91055	33.91634	0.49360
4	nbar0	0.54816	-0.06834	-1.20905	1.62781	0.93957
5	pi0	-0.37380	0.02504	0.35486	0.53338	0.13498
6	n0	-0.08115	-0.02823	-0.53314	1.08370	0.93957
7	pi-	-0.23393	0.11296	-5.76403	5.77157	0.13957
8	K-	-0.00627	-0.15812	-44.71705	44.72006	0.49360
9	K+	-0.03848	-0.01139	-64.08264	64.08456	0.49360
10	pi-	-0.02479	0.08067	-2.09126	2.09761	0.13957
11	pi+	-0.41465	-0.13479	-8.29972	8.31234	0.13957
12	pi0	-0.50854	0.11826	-18.60847	18.61629	0.13498
13	pi-	-0.04847	0.20076	-3.15301	3.16285	0.13957
14	pi0	0.76201	-0.09810	-3.33633	3.42631	0.13498
15	K-	-0.08212	0.24522	0.71152	0.90376	0.49360
16	pi+	0.09763	-0.21837	0.15468	0.31721	0.13957
17	pi+	-0.14039	0.17750	0.46433	0.53507	0.13957
18	pi0	0.23292	-0.41112	2.88185	2.92345	0.13498
19	pi+	-0.17876	-0.03157	6.10565	6.10994	0.13957
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22	pi0	-0.16321	-0.13453	0.64843	0.69528	0.13498
23	pi0	-0.14686	-0.00214	0.56642	0.60052	0.13498
24	pi-	-0.01222	-0.27842	0.19750	0.36899	0.13957
25	K_L0	-0.45356	0.56332	4.42730	4.51350	0.49767
26	pi+	-0.17413	-0.00385	-0.03275	0.22559	0.13957
27	pi0	0.21046	-0.04576	-1.03674	1.06744	0.13498
28	pi-	0.04562	-0.11103	1.10752	1.12271	0.13957
29	pi+	-0.15254	0.27925	1.58019	1.61794	0.13957
30	pi+	0.00633	0.23779	-20.99897	21.00078	0.13957
31	pi-	0.09527	-0.14227	-9.49998	9.50254	0.13957
32	pi-	0.39307	0.13431	0.53495	0.69152	0.13957
33	pi+	0.29351	-0.13195	0.09074	0.36231	0.13957
sum momentum		0.00000	0.00000	0.00000	900.00000	900.00000

```
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 1  p+             0.18101    -0.23124    427.60408    427.60521   0.93827
 2  p+            -0.06244    -0.10079   -231.29111    231.29304   0.93827
 3  K+             0.33646     0.18878    -33.91055     33.91634   0.49360
 4  nbar0          0.54816    -0.06834     -1.20905      1.62781   0.93957
 5  pi0           -0.37380     0.02504      0.35486      0.53338   0.13498
 6  n0            -0.08115    -0.02823     -0.53314      1.08370   0.93957
 7  pi-           -0.23393     0.11296     -5.76403      5.77157   0.13957
 8  K-            -0.00627    -0.15812    -44.71705     44.72006   0.49360
 9  K+            -0.03848    -0.01139    -64.08264     64.08456   0.49360
10  pi-           -0.02479     0.08067     -2.09126      2.09761   0.13957
11  pi+           -0.41465    -0.13479     -8.29972      8.31234   0.13957
12  pi0           -0.50854     0.11826    -18.60847     18.61629   0.13498
13  pi-           -0.04847     0.20076     -3.15301      3.16285   0.13957
14  pi0            0.76201    -0.09810     -3.33633      3.42631   0.13498
15  K-            -0.08212     0.24522      0.71152      0.90376   0.49360
16  pi+                                                            0.13957
17  pi+                                                            0.13957
18  pi0            0.23292    -0.41112      2.88185      2.92345   0.13498
19  pi+           -0.17876    -0.03157      6.10565      6.10994   0.13957
20  pi-            0.03074     0.07151      0.33071      0.36729   0.13957
21  pi0            0.06314    -0.09334      0.80407      0.82307   0.13498
22  pi0           -0.16321    -0.13453      0.64843      0.69528   0.13498
23  pi0           -0.14686    -0.00214      0.56642      0.60052   0.13498
24  pi-           -0.01222    -0.27842      0.19750      0.36899   0.13957
25  K_L0          -0.45356     0.56332      4.42730      4.51350   0.49767
26  pi+           -0.17413    -0.00385     -0.03275      0.22559   0.13957
27  pi0            0.21046    -0.04576     -1.03674      1.06744   0.13498
28  pi-            0.04562    -0.11103      1.10752      1.12271   0.13957
29  pi+           -0.15254     0.27925      1.58019      1.61794   0.13957
30  pi+            0.00633     0.23779    -20.99897     21.00078   0.13957
31  pi-            0.09527    -0.14227     -9.49998      9.50254   0.13957
32  pi-            0.39307     0.13431      0.53495      0.69152   0.13957
33  pi+            0.29351    -0.13195      0.09074      0.36231   0.13957
sum momentum       0.00000     0.00000      0.00000    900.00000  900.00000
```
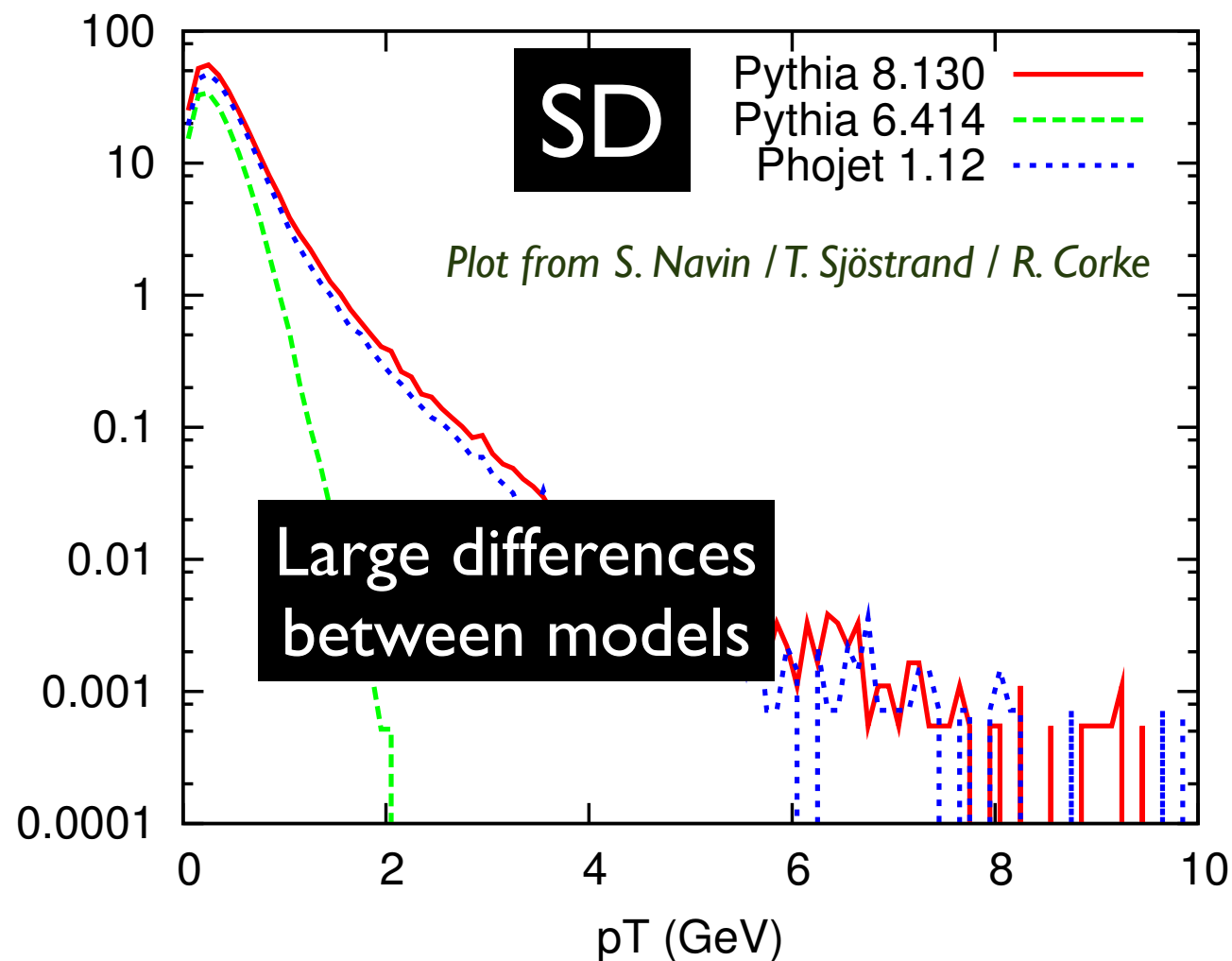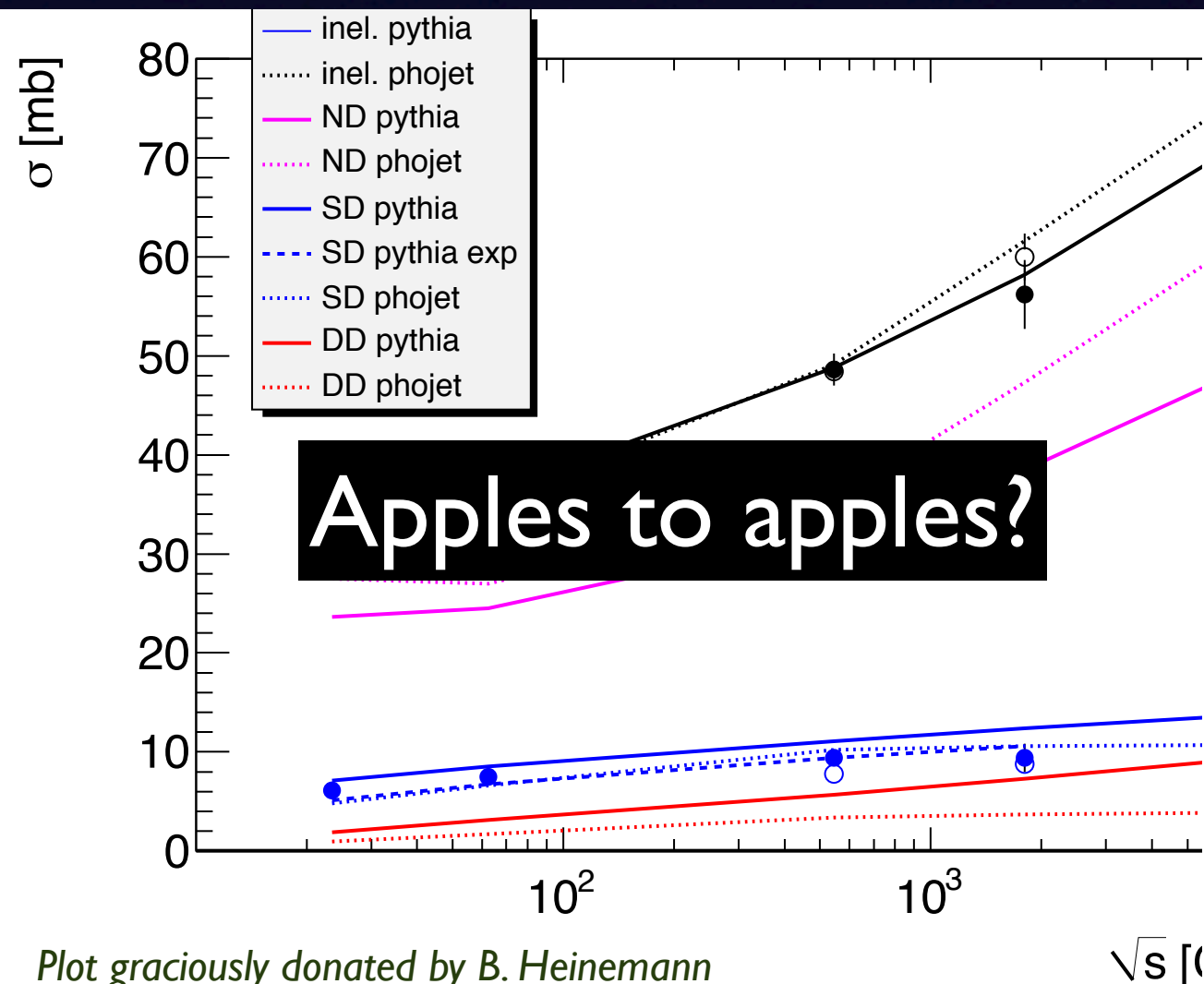
MC "Truth" : Single Diffractive

```
 I   particle/jet  P(I,1)        P(I,2)        P(I,3)        P(I,4)        P(I,5)
 1   p+            0.18101       -0.23124      427.60408     427.60521     0.93827
 2   p+            -0.06244      -0.10079      -231.29111    231.29304     0.93827
```

Moral: What some theorist/model defines as SD, DD, etc, *is not itself a physical observable!*

Tails of one are *indistinguishable* from the other (even with a perfect detector with full PID)

If no physical measurement can tell the difference, it does not make sense to correct back to

```
 25  K_l0          -0.45356      0.56332       4.42730       4.51350       0.49767
```

And this is even assuming we had the perfect model on which everyone agrees ...

```
 33  pi+           0.29351       -0.13195      0.09074       0.36231       0.13957
 sum momentum       0.00000       0.00000       0.00000       900.00000     900.00000
```

Ways Out

A) Trust the theorists. Correct to specific set of fundamental processes ➡ NSD, INEL, ...
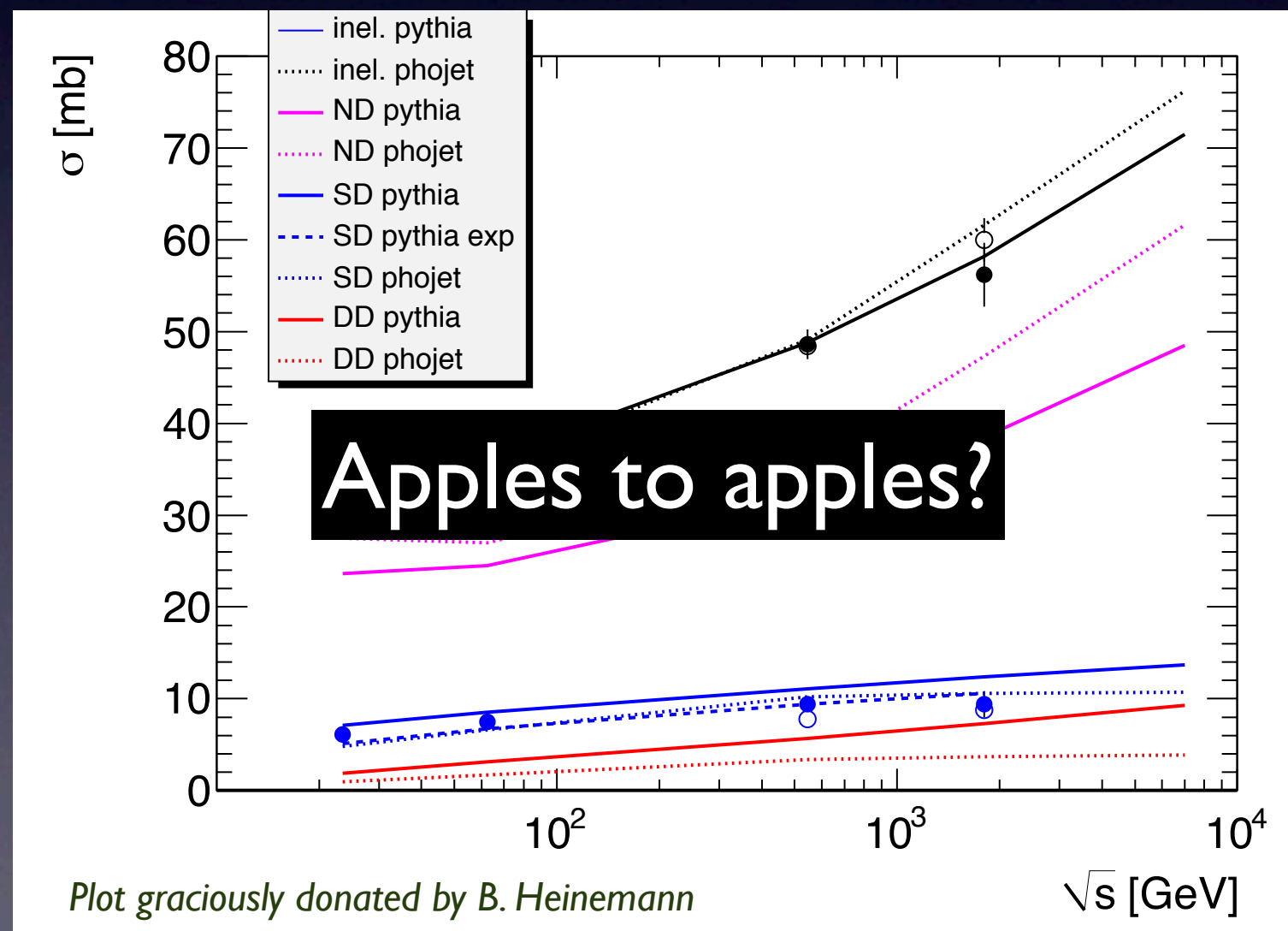
Plot graciously donated by B. Heinemann

Ways Out

A) Trust the theorists. Correct to specific set of fundamental processes ➡ NSD, INEL, ...

Plot graciously donated by B. Heinemann

Plot from S. Navin / T. Sjöstrand / R. Corke

Ways Out

A) Trust the theorists. Correct to specific set of fundamental processes ➡ NSD, INEL, ...

Traditional, but not optimal
- Defs of SD, DD, ND, etc, are MODEL-DEPENDENT
- Models DO NOT AGREE
- E.g., "NSD" is not a physical definition, unless defined in terms of hadron-level cuts

Note: diffraction is not, itself, "the evil guy" here. A clear hadron-level definition would also bring diffractive studies on a better, more model-independent, footing.

Ways Out

A) Trust the theorists. Correct to specific set of fundamental processes ➡ NSD, INEL, …

B) Report a measurement with a given set of hadron-level cuts ➡ "fiducial" MB

Employed in the third LHC paper
ATLAS Collaboration, preliminary

Ways Out

B) Report a measurement with a given set of hadron-level cuts ➡ "fiducial" MB
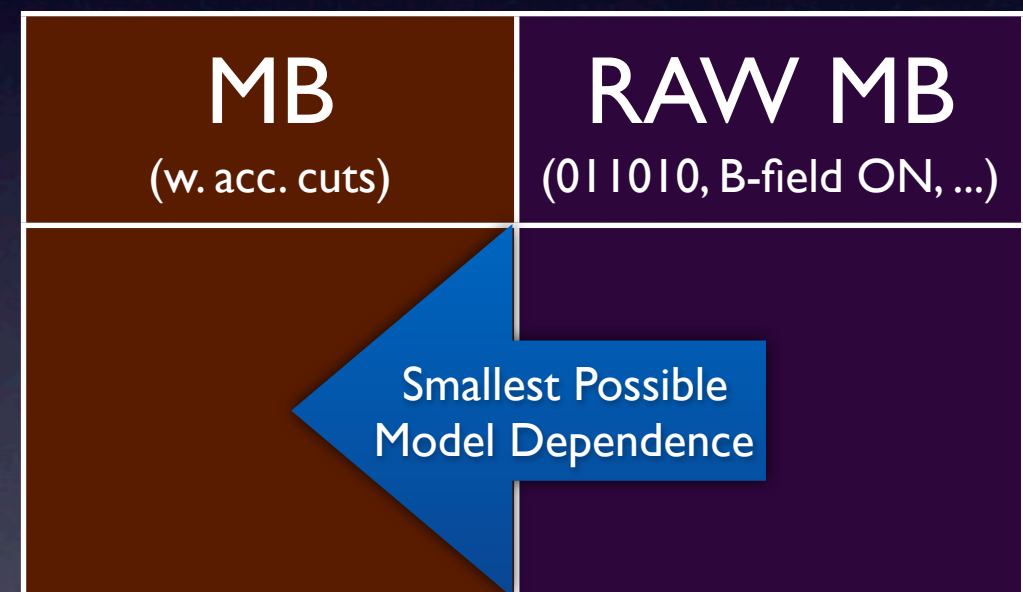
Track reconstruction efficiency as fct of pT, eta corrected to Theta function (|eta| < Y, pT > X)

Trigger efficiency corrected to Theta function (at least M tracks with X pT in phase-space region Y, or similar)
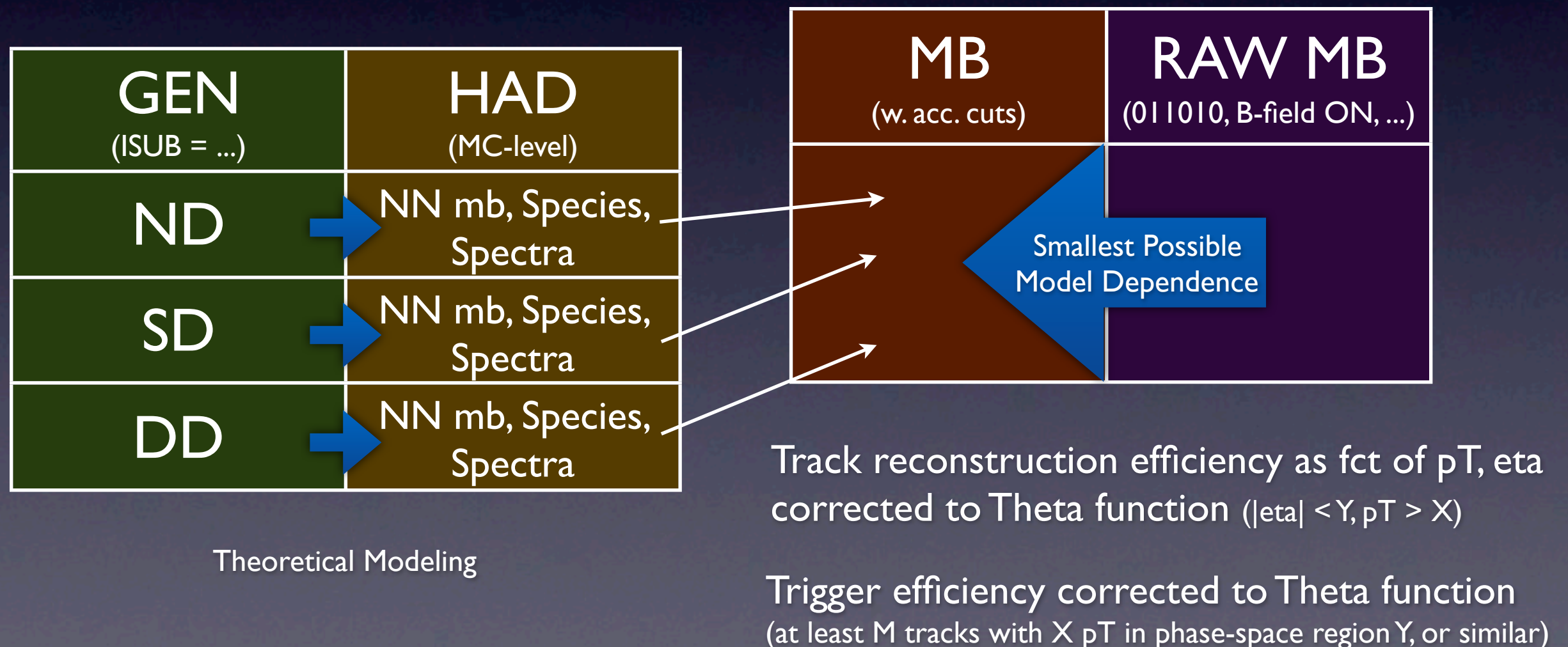
Ways Out

B) Report a measurement with a given set of hadron-level cuts ➡ "fiducial" MB

Drawbacks?

- "MB" is not "ZB"
- "MB" is acc/trig-dependent mixture of SD, DD, ND
- **How to compare** with other measurements or "GEN"-level theory cross sections (e.g., sigmaDiff)?
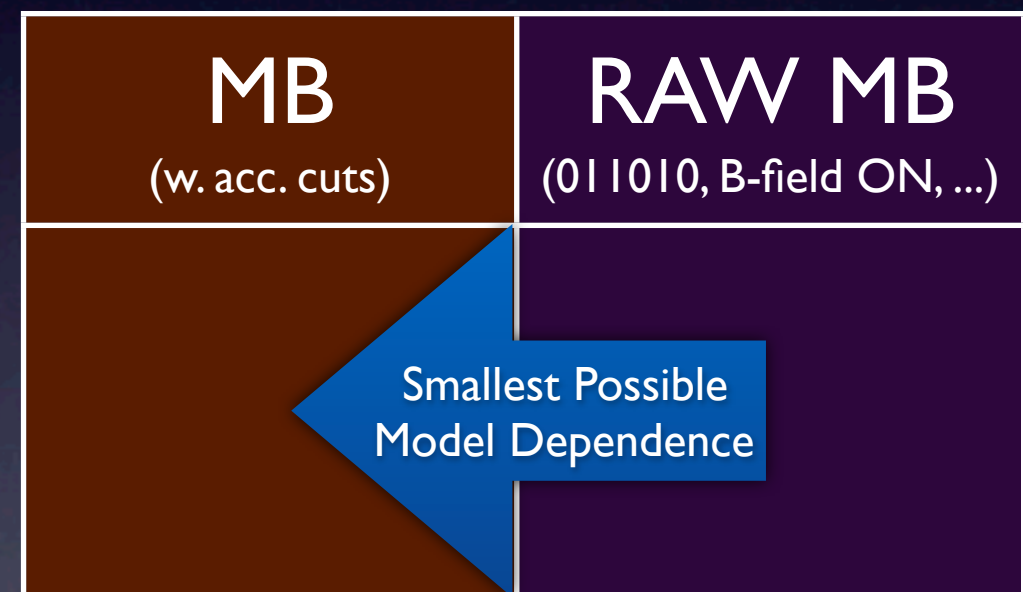
MB (w. acc. cuts)	RAW MB (011010, B-field ON, ...)

Smallest Possible Model Dependence

Track reconstruction efficiency as fct of pT, eta corrected to Theta function ($|eta| < Y$, $pT > X$)

Trigger efficiency corrected to Theta function (at least M tracks with X pT in phase-space region Y, or similar)

Ways Out

B) Report a measurement with a given set of hadron-level cuts ➡ "fiducial" MB

Drawbacks?

- MB *was never* ZB (clear & simple event selection criteria = good enough)

- Mixture of SD, DD, ND in given region = **modeling aspect**
  - The most you can do is optimize selection to *enhance*, e.g., "ND", "SD", ...

- **HAD-level observables** and event-sample definitions give us *not* a ready-made solution but:
  - **A well-defined measurement** and reference for posterity ...
  - **With the smallest** possible uncertainties ...
  - **A *base for*** comparisons to other definitions (other exps / TH defs)

Ways Out

C) More information? Partition MB sample into various "enriched" samples?

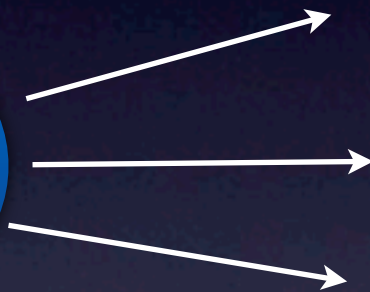Systematically introduce "biases" → MB

Ways Out

C) More information? Partition MB sample into various "enriched" samples?

Systematically introduce "biases" ➡️ **MB**

➡️ SD-Enriched HAD-level sample *(cannot be 100% Use models to estimate best purity)* **More sensitive to SD** cross section. **Report observed cross section**, then translate to SD-GEN-level cross section using best models of the day. **(Don't just tell us the latter.)**

➡️ ND-Enriched HAD-level sample (can be almost 100%)
(... + ... Central-Diffraction-Enhanced, DD-Enhanced, "HARD", ...)

Ways Out

C) More information? Partition MB sample into various "enriched" samples?

Systematically introduce "biases" ➡ MB

➡ SD-Enriched HAD-level sample *(cannot* be 100% Use models to estimate best purity)
More sensitive to SD cross section. **Report observed cross section**, then translate to SD-GEN-level cross section using best models of the day. **(Don't just tell us the latter.)**

➡ ND-Enriched HAD-level sample (can be almost 100%)
(... + ... Central-Diffraction-Enhanced, DD-Enhanced, "HARD", ...)

How to compare between experiments?

Recommendations from the UE/MB WG Meeting
March 1-2 2010, CERN

Note: these are just recommendations for observables that can be useful for the explicit purpose of *comparisons and cross checks* between the experiments at the LHC.

They are in no way intended to limit or impose on what the individual experiments could/should pursue

Event Samples

- **<u>Define physical "MB500" and "MB900"</u>** samples by: at least one charged particle in |eta|<1 with p_T > 0.5 and 0.9 GeV, respectively
  Feasible for ATLAS, ALICE, CMS. *Still need particle-level MB definition for LHCb*

- **<u>Also extrapolate to</u>** "INEL" event sample
  Feasible for all 4 experiments - for comparisons including "zero bin", and for older measurements

- **<u>Optionally include</u>**

  - "NSD" sample (with caveats)

  - "HC2" sample with 2 or more particles in |eta|<1.0 ? (suppresses diff)

  - "HC3" sample with 3 or more particles in |eta|<1.0 ? (even more bias)

  - Still need particle-level definition of **diffractively *enhanced*** samples ...

Corrections

- **Use the same** model for all corrections

  - *(Regardless of whether it is the best possible - main point here is that different models do not produce artificial differences)*

- Inelastic Non-Diffractive: PYTHIA 6.422, Tune Perugia 0 (MSTP(5)=320)

  PS, arXiv:0905.3418 + in preparation

- Diffractive modeling to be discussed at Tools Readiness workshop March 29-31

Charged Track Definition

- **N_{ch} counts *all*** charged particles (including leptons)

- **Particles with lifetimes** longer than c*tau = 10 mm are treated as stable:

$$(\mu^{\pm}, \pi^{\pm}, K_S^0, K_L^0, n^0, \Lambda^0, \Sigma^{\pm}, \Xi^0, \Xi^{\pm}, \text{and } \Omega^{\pm})$$

- (Note: pi^0 decays must also be included in model comparisons, since there is a per-cent level branching fraction to charged leptons)
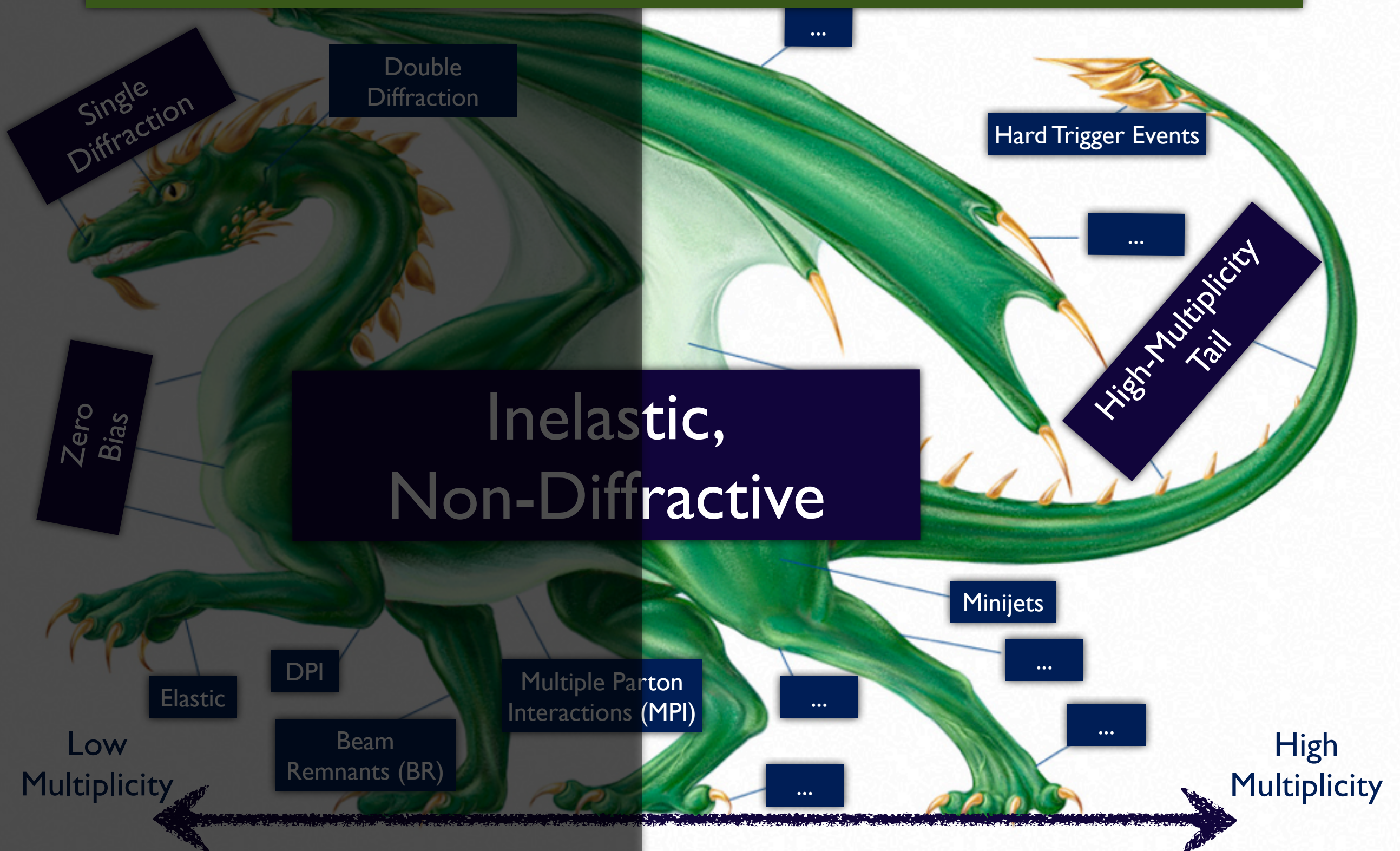
Observables

- $dN_{ch}/d(eta)$ for the largest eta range possible in the experiment, for tracks with $p_T > 0.5$ and 0.9 GeV/c
  for INEL (overlaps with LHCb) and for MB500 and MB900, respectively, for ALICE, ATLAS, CMS

- $dN_{ch}/d(p_T)$ for tracks inside $|eta| < 1.0$, down to as low p_T as possible in the experiment
  for ALICE, ATLAS, CMS + in a region around eta = 2 (INEL only?) for comparison to LHCb

- $<p_T>(N_{ch})$ for tracks inside $|eta| < 1.0$, including tracks with $p_T > 0.5$ and 0.9 GeV
  for ALICE, ATLAS, CMS for MB500 and MB900, respectively + in a region around eta = 2 (INEL?) for comparison to LHCb

- $P(N_{ch})$ for $|eta| < 1.0$
  for ALICE, ATLAS, CMS for each sample separately + in a region around eta = 2 (INEL?) for comparison to LHCb

To go further ...

- **This was just** a minimal list

- **Using the strengths** of the individual experiments, we can go much further in our efforts to constrain theory!
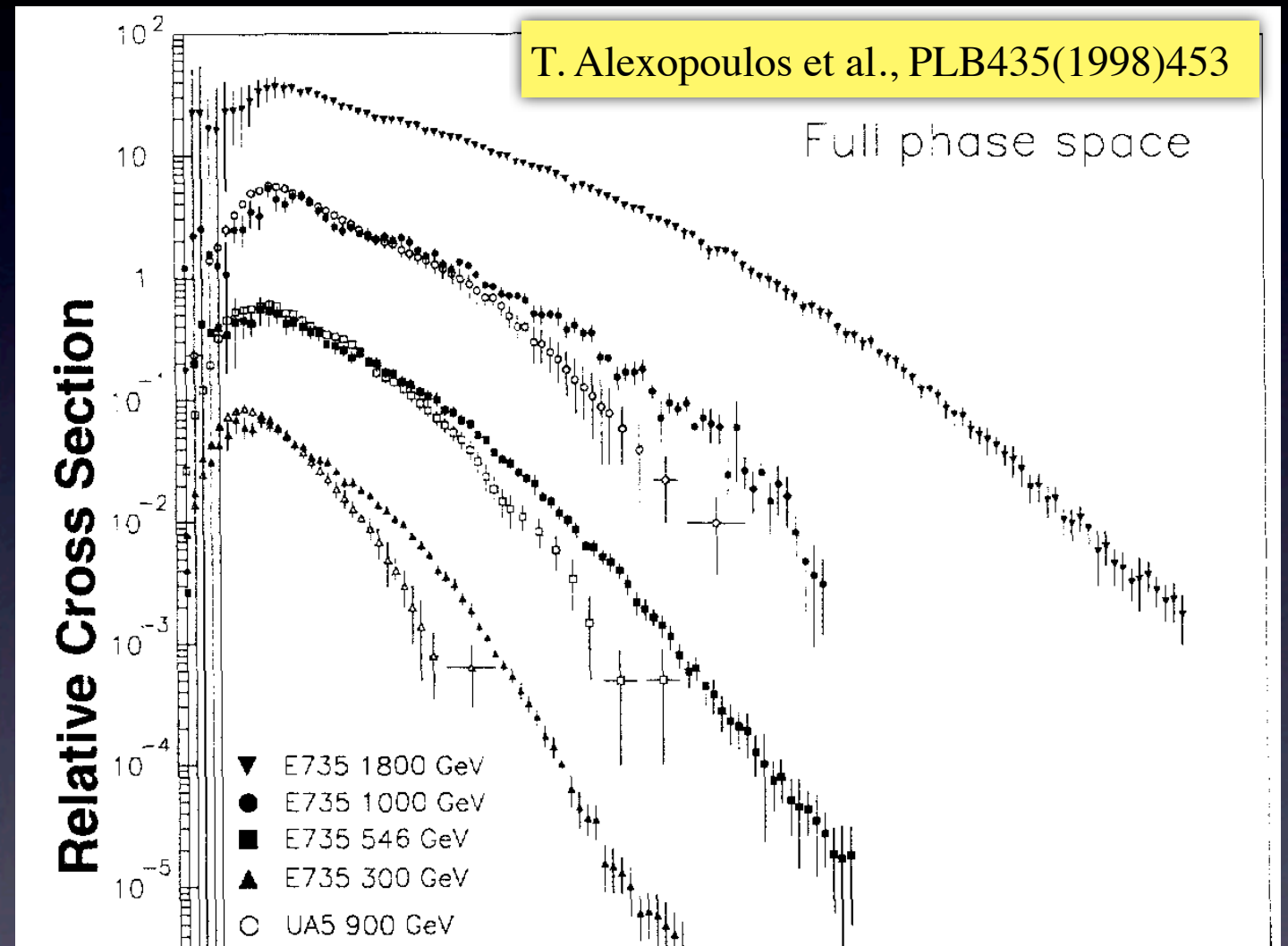
Issues at High Multiplicity

Single Diffraction

Double Diffraction

...

Hard Trigger Events

...

High-Multiplicity Tail

Zero Bias

Inelastic, Non-Diffractive

Minijets

...

DPI

Elastic

Multiple Parton Interactions (MPI)

...

...

Beam Remnants (BR)

...

Low Multiplicity

High Multiplicity

High Multiplicities:
An Unresolved Question
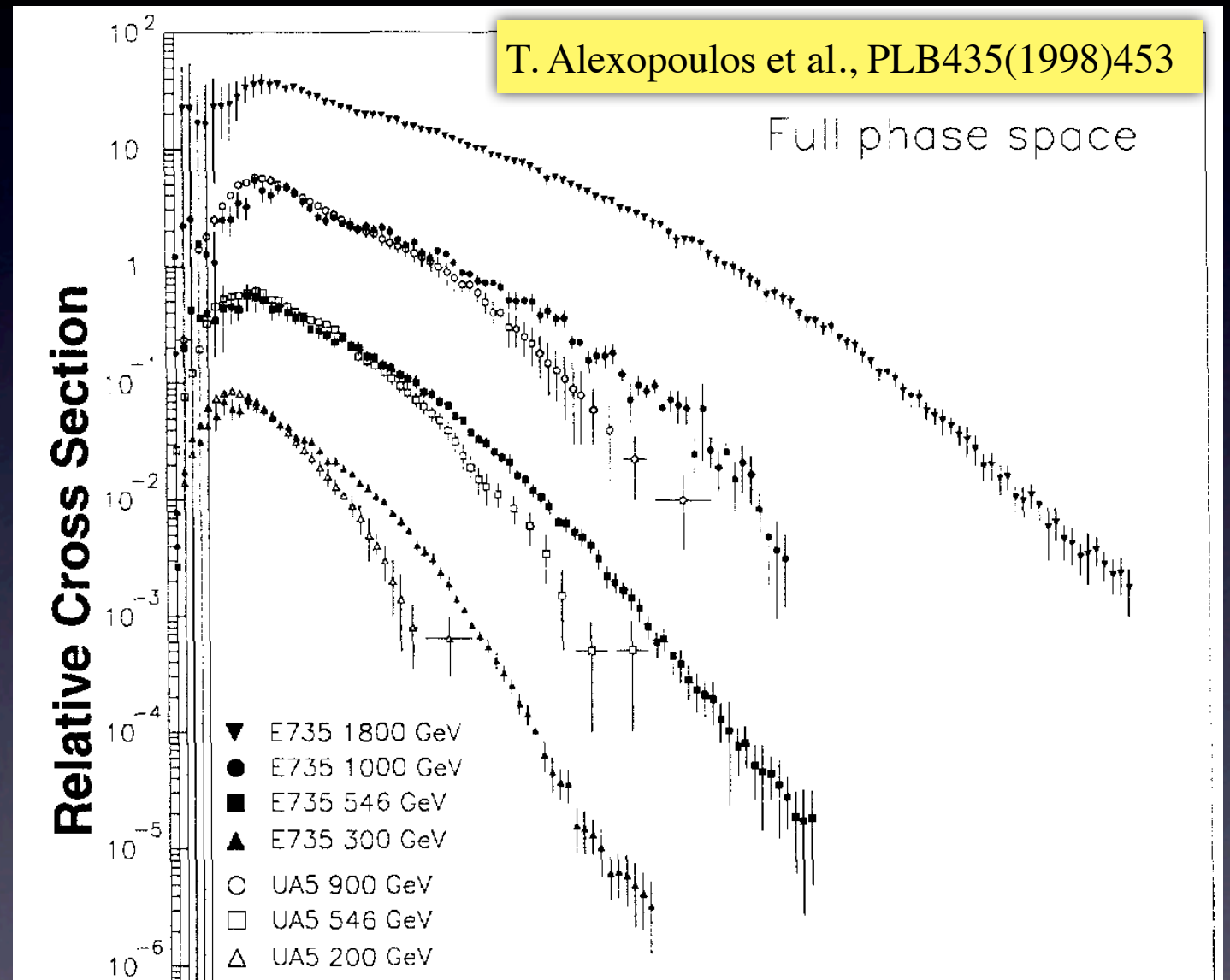
- UA5 at 200, 546, and 900 GeV

- E735 at 300, 546, 1000, and 1800 GeV

- Mutually Inconsistent over *Entire Range*

T. Alexopoulos et al., PLB435(1998)453

High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV

- E735 at 300, 546, 1000, and 1800 GeV
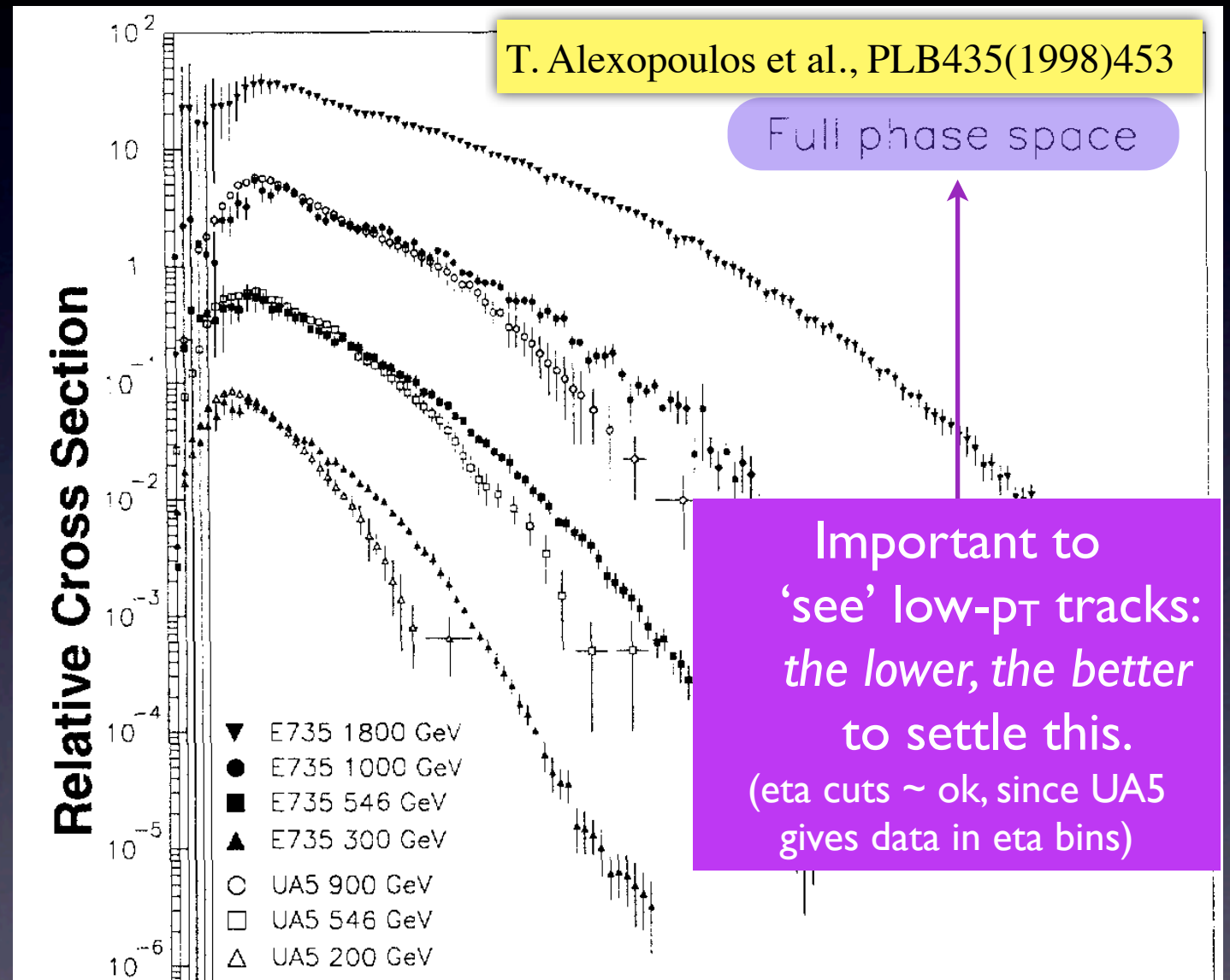
- Mutually Inconsistent over *Entire Range*

T. Alexopoulos et al., PLB435(1998)453

Full phase space

Relative Cross Section
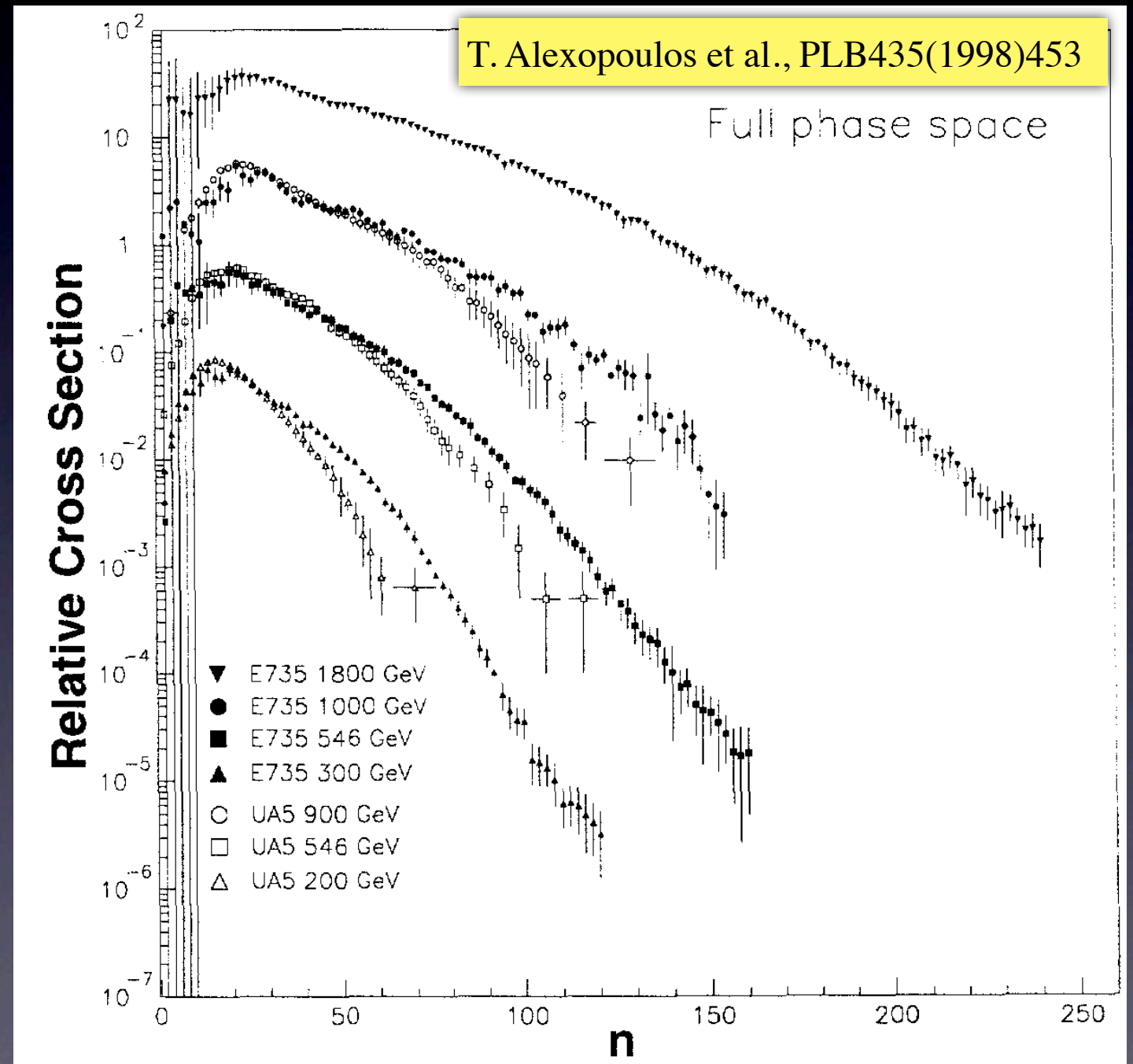
- ▼ E735 1800 GeV
- ● E735 1000 GeV
- ■ E735 546 GeV
- ▲ E735 300 GeV
- ○ UA5 900 GeV

Without even knowing how many tracks to tune to, how could we hope to constrain non-perturbative models (i.e., Monte Carlos) ?

High Multiplicities:
An Unresolved Question

- UA5 at 200, 546, and 900 GeV

- E735 at 300, 546, 1000, and 1800 GeV

- Mutually Inconsistent over *Entire Range*

T. Alexopoulos et al., PLB435(1998)453

Full phase space

Relative Cross Section

▼ E735 1800 GeV
● E735 1000 GeV
■ E735 546 GeV
▲ E735 300 GeV
○ UA5 900 GeV
□ UA5 546 GeV
△ UA5 200 GeV

Again: LHC Measurements at 900 and 2360 GeV are *the only way* to settle this question once and for all

High Multiplicities: An Unresolved Question

- UA5 at 200, 546, and 900 GeV

- E735 at 300, 546, 1000, and 1800 GeV

- Mutually **Inconsistent over** *Entire Range*

T. Alexopoulos et al., PLB435(1998)453

Full phase space

Relative Cross Section

▼ E735 1800 GeV
● E735 1000 GeV
■ E735 546 GeV
▲ E735 300 GeV

○ UA5 900 GeV
□ UA5 546 GeV
△ UA5 200 GeV

Important to 'see' low-p_T tracks: *the lower, the better* to settle this.
(eta cuts ~ ok, since UA5 gives data in eta bins)

Again: LHC Measurements at 900 and 2360 GeV are *the only way* to settle this question once and for all

Fragmentation

- Normal MC Tuning Procedure:

    - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)
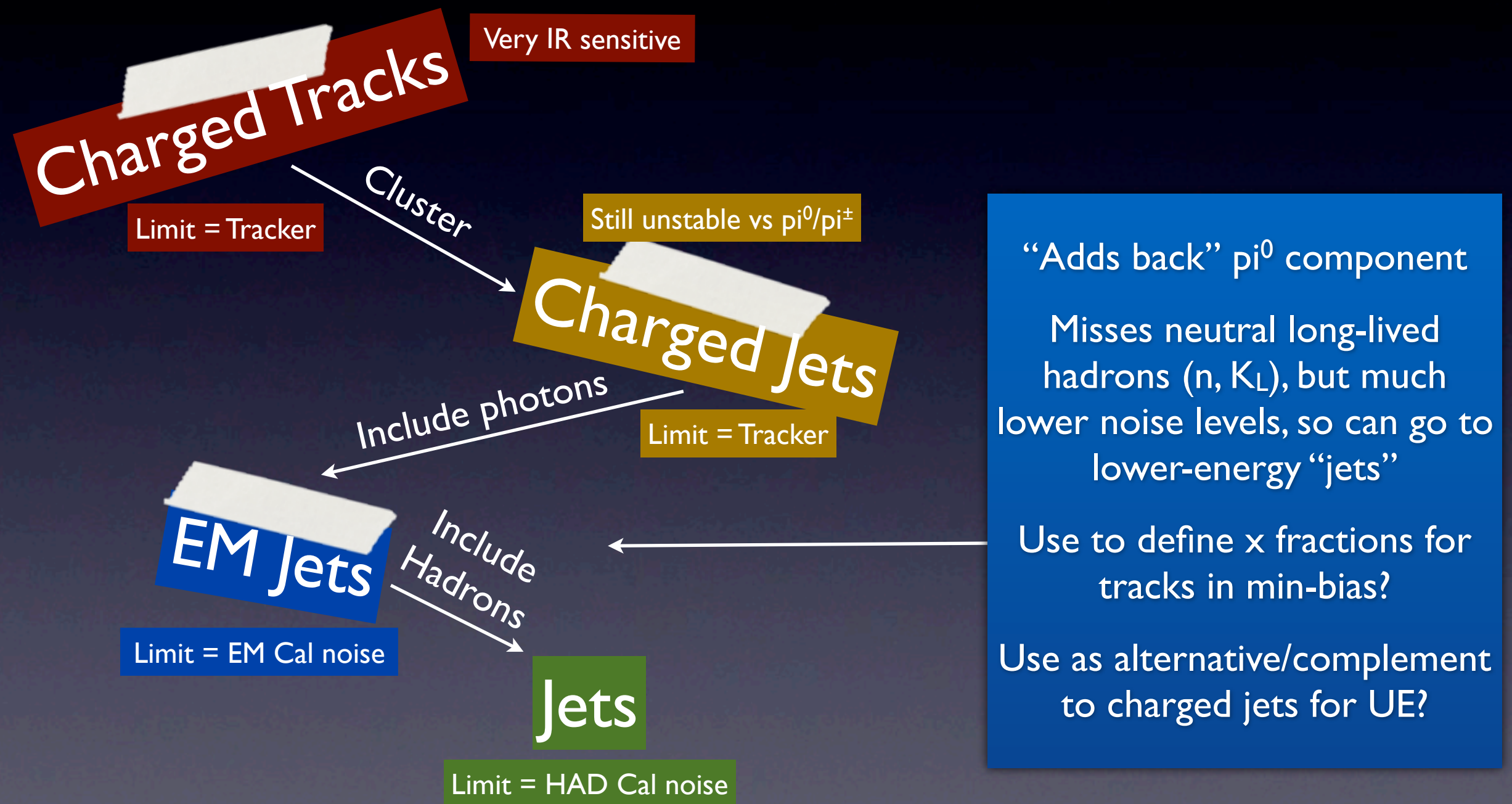
Fragmentation

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    - But pp/ppbar is a very different environment, at the infrared level!
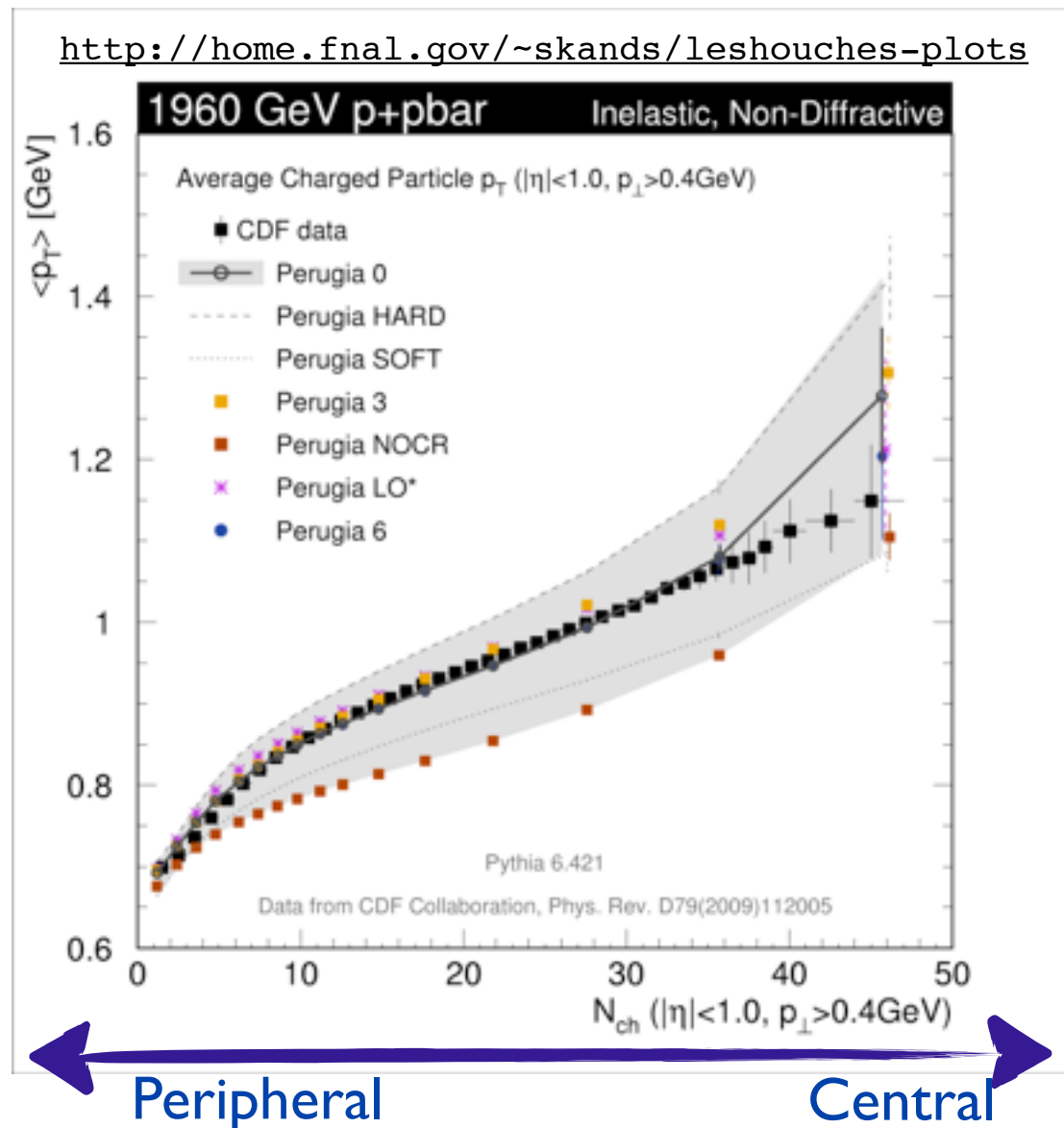
Fragmentation

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  - Check fragmentation *in situ* at hadron colliders

    - N and p_T spectra (and x spectra normalized to 'jet'/minijet energy?) **Identified particles** highly important to dissect fragmentation

The Road to Infrared Safety
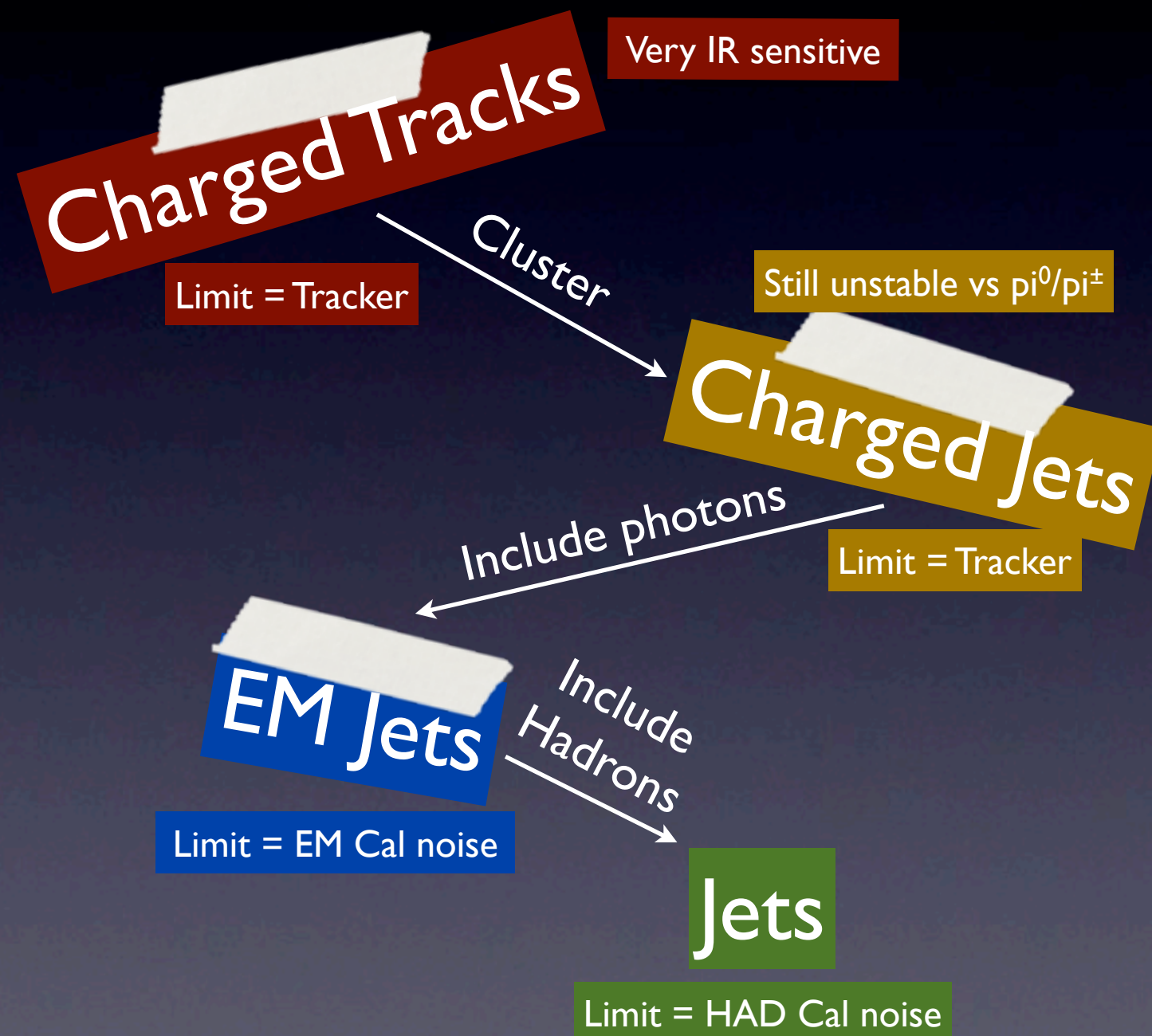
Charged Tracks

Very IR sensitive

Limit = Tracker

Cluster

Still unstable vs pi^0/pi$^\pm$

Charged Jets

Limit = Tracker

Include photons

EM Jets

Limit = EM Cal noise

Include Hadrons

Jets

Limit = HAD Cal noise

The Road to Infrared Safety

Charged Tracks

Very IR sensitive

Limit = Tracker

Cluster →

Still unstable vs pi^0/pi$^\pm$

Charged Jets

Limit = Tracker

Include photons →

EM Jets

Limit = EM Cal noise

Include Hadrons →

Jets

Limit = HAD Cal noise

"Adds back" pi^0 component

Misses neutral long-lived hadrons (n, K_L), but much lower noise levels, so can go to lower-energy "jets"

Use to define x fractions for tracks in min-bias?

Use as alternative/complement to charged jets for UE?

Fragmentation

- Normal MC Tuning Procedure:

  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)

    - But pp/ppbar is a very different environment, at the infrared level!

  - Check fragmentation *in situ* at hadron colliders

    - N and p_T spectra (and x spectra normalized to 'jet'/minijet energy?) **Identified particles** highly important to dissect fragmentation

    - (How) do the spectra change with (pseudo-)rapidity? (different dominating production/fragmentation mechanisms as fct of rapidity? E.g., compare LHCb with central?)

    - How do they change with event activity? (cf. heavy-ion ~ central vs peripheral collisions, hard trigger event (UE))

Change with Event Activity

- One (important) example: $\langle p_T \rangle (N_{ch})$

http://home.fnal.gov/~skands/leshouches-plots

1960 GeV p+pbar — Inelastic, Non-Diffractive

Average Charged Particle p_T ($|\eta|<1.0$, $p_\perp>0.4$GeV)

- CDF data
- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia 3
- Perugia NOCR
- Perugia LO*
- Perugia 6

Pythia 6.421
Data from CDF Collaboration, Phys. Rev. D79(2009)112005

Peripheral ← → Central

The p_T spectrum becomes harder as we increase N_{ch}.

Important tuning reference (highly non-trivial to describe correctly)

(Color reconnections, string interactions, rescattering, collective flow in pp, ...?)

Fragmentation

- Normal MC Tuning Procedure:

  - Fragmentation and Flavour parameters constrained at LEP, then used in pp/ppbar (Jet Universality)

    - But pp/ppbar is a very different environment, at the infrared level!

  - Check extrapolation to forward region

    - Subir's synergy with Cosmic Ray Fragmentation

    - 'New' Physics: collective effects, multiple scatterings, low-x evolution, BFKL, ..., but central region remains important testing ground

(Additional Observables)

- **Particle-Particle Correlations** probe fragmentation beyond single-particle level. E.g.,:

  - A baryon here, where's the closest antibaryon?

    - + Is the Baryon number of the beam carried into the detector?

  - A Kaon here, where's the closest strange particle?

    - + Multi-Strange particles. Over how big a distance is the strangeness 'neutralized'?

  - Charge correlations. Special case: is the charge of the beam carried into the detector?

Baryon Transport

- Models disagree wildly.

- Don't listen to them

- (Still, can be used to gauge possible size of effect)

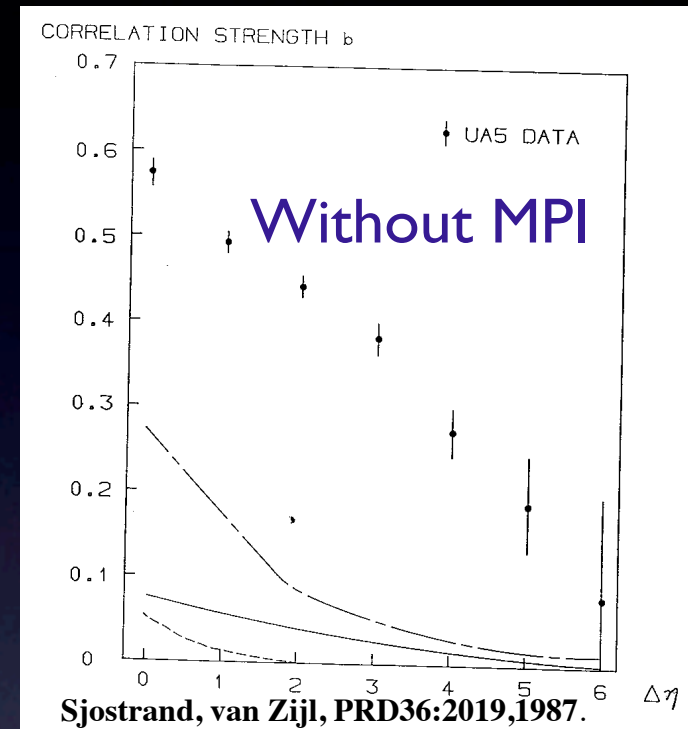900 GeV p+p — Inelastic, Non-Diffractive

Λ^0bar / Λ^0 η Distribution (generator-level)

Legend:
- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia NOCR
- DW

Pythia 6.422

Baryon Transport

- Models disagree wildly.

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- (Still, can be used to gauge possible size of effect)

7 TeV p+p   Inelastic, Non-Diffractive

Λ^0bar / Λ^0 η Distribution (generator-level)

$N(\Lambda^0$bar$)/N(\Lambda^0)$

Non-trivial energy evolution

Legend:
- Perugia 0
- Perugia HARD
- Perugia SOFT
- Perugia NOCR
- DW

Pythia 6.422

η
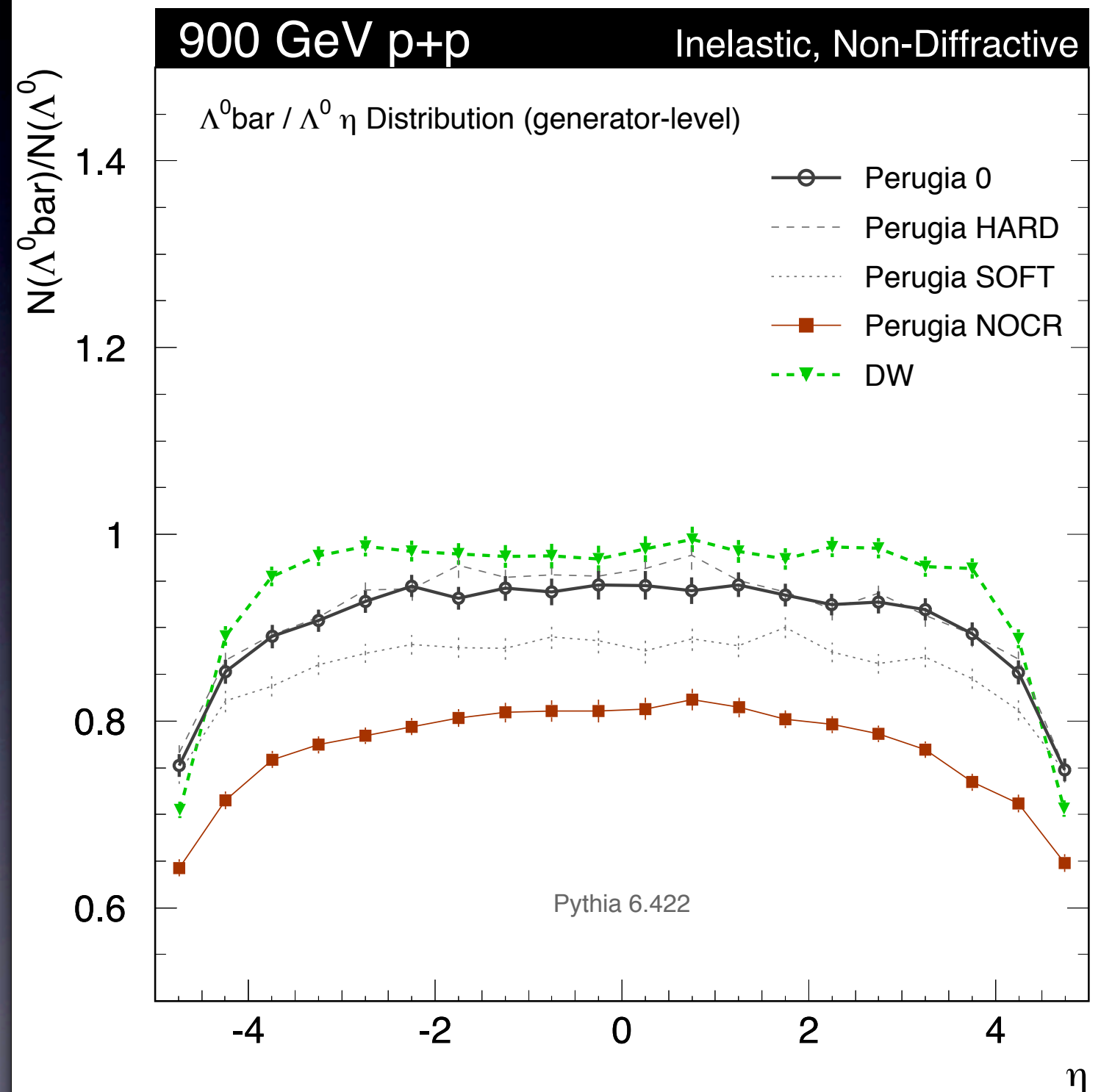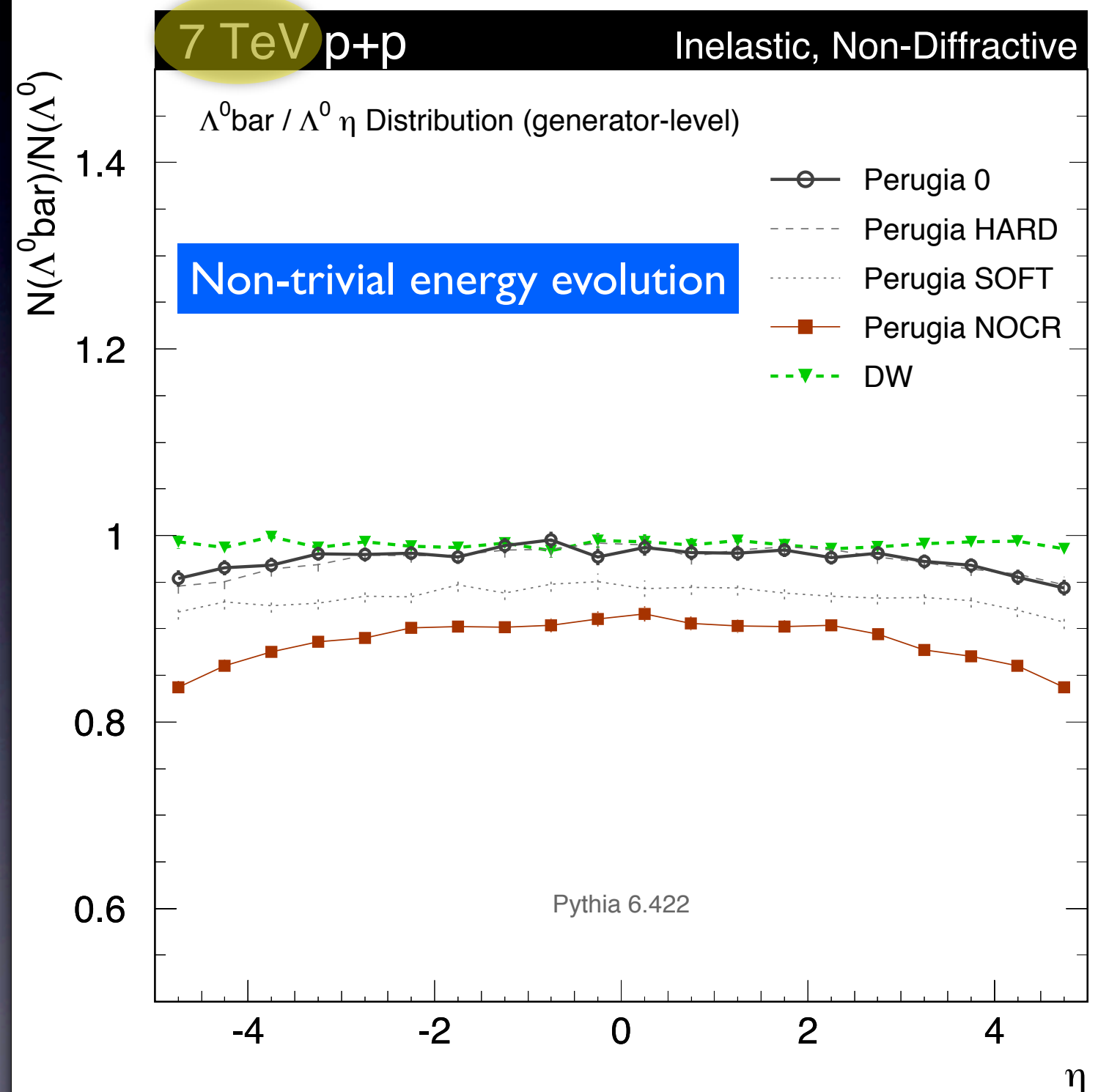
Baryon Transport

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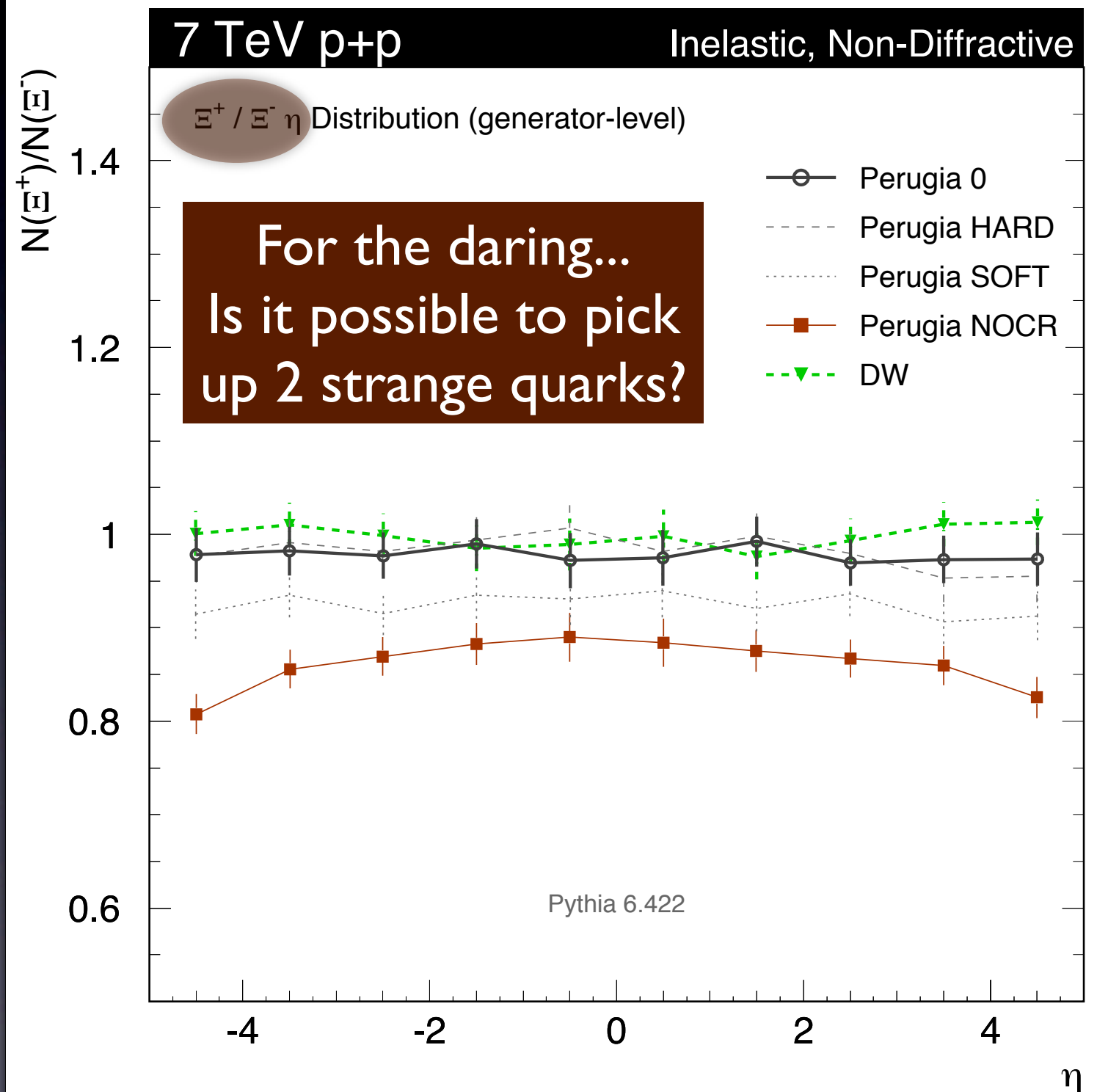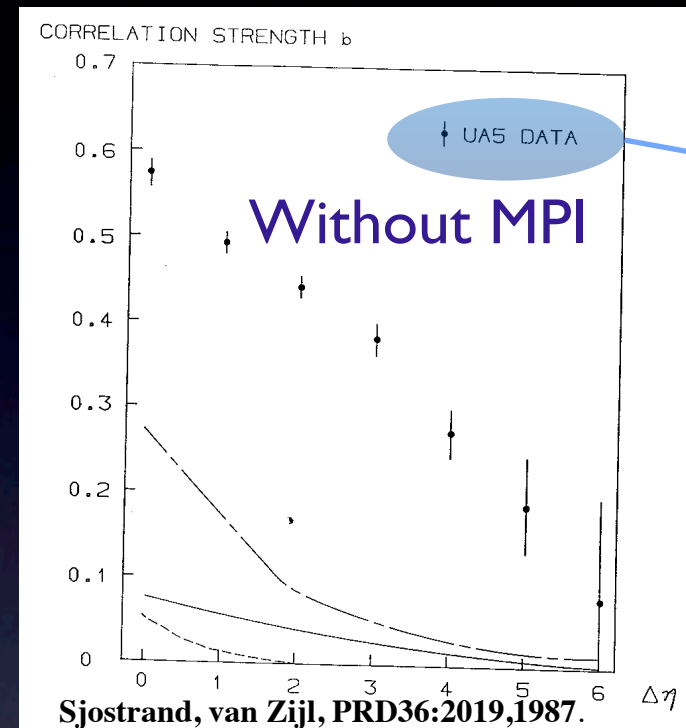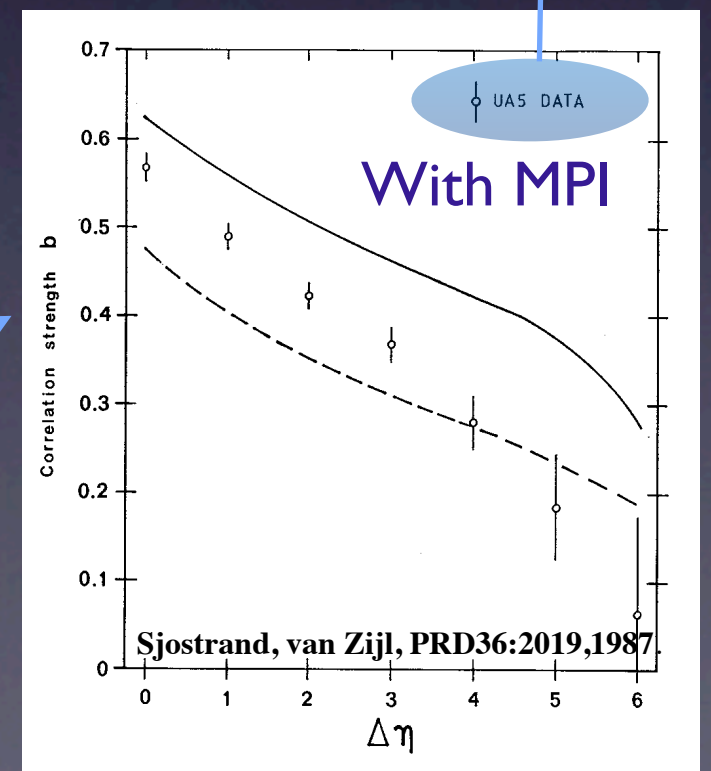
Radiation vs MPI

- What is producing the tracks?

    - Is it **Radiation**? (tends to produce partons close in phase space)

    - Or is it **MPI**? (partons going out in opposite directions)

    - Or is it soft production between the **remnants**?
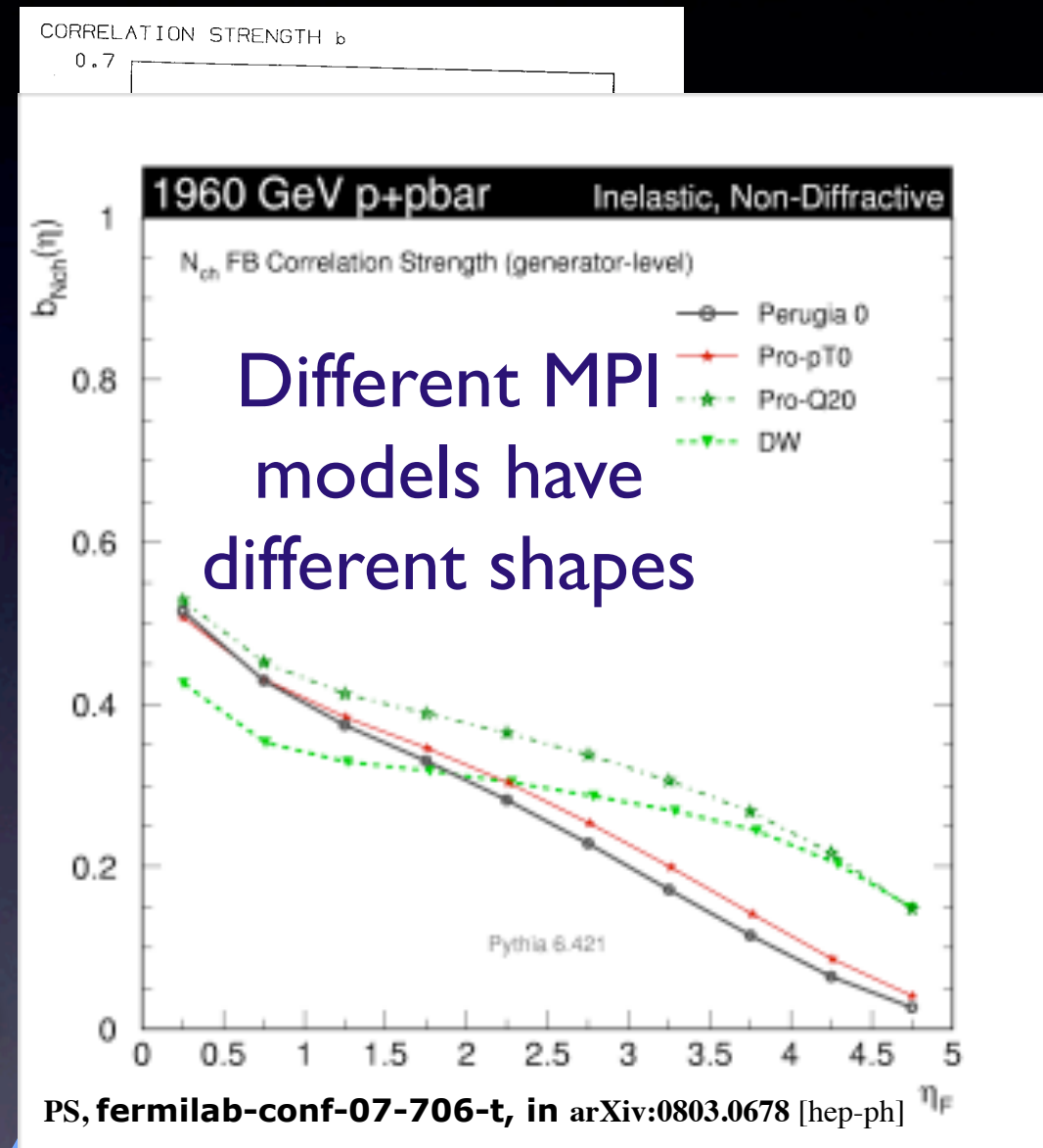
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- **Probing long- vs short-distance correlations can tell us!**

  - E.g., forward-backward correlation, *b*

CORRELATION STRENGTH b

‡ UA5 DATA

Without MPI

Sjostrand, van Zijl, PRD36:2019,1987.

$\Delta\eta$

‡ UA5 DATA

With MPI

Correlation strength b

Sjostrand, van Zijl, PRD36:2019,1987.

$\Delta\eta$

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$
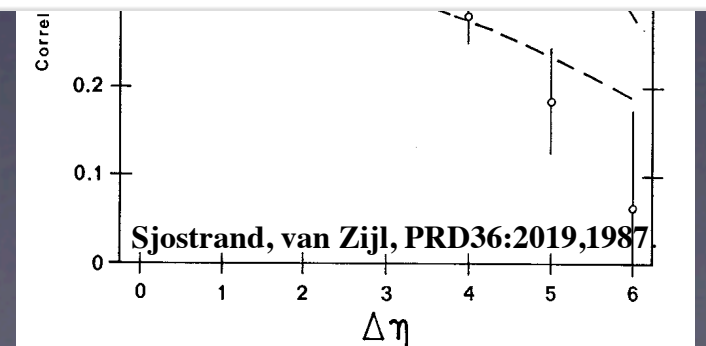
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CORRELATION STRENGTH b

UA5 DATA

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Sjostrand, van Zijl, PRD36:2019,1987.
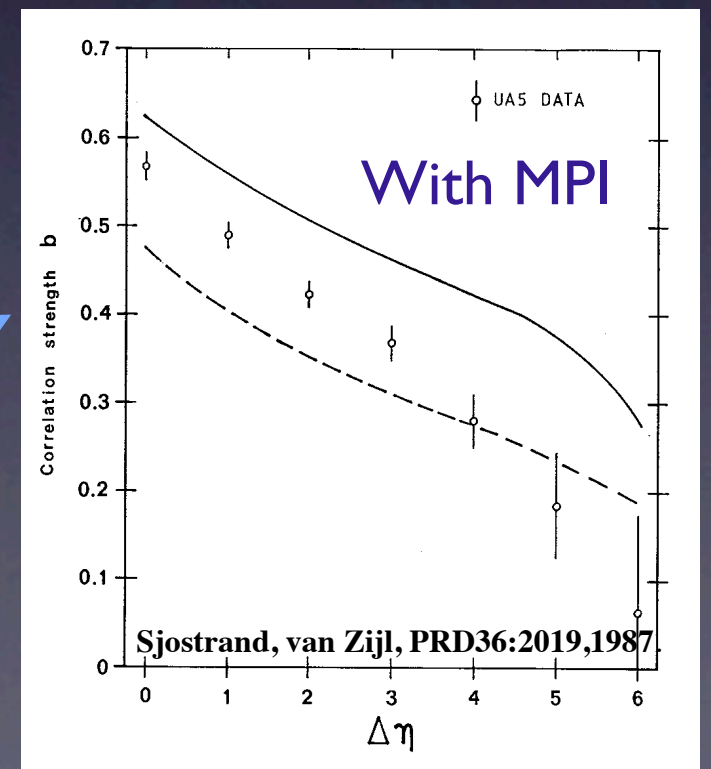
b Not measured at Tevatron

UA5 DATA

With MPI

Correlation strength b

Sjostrand, van Zijl, PRD36:2019,1987

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$

Radiation vs MPI

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CORRELATION STRENGTH b

1960 GeV p+pbar — Inelastic, Non-Diffractive

N_{ch} FB Correlation Strength (generator-level)

- Perugia 0
- Pro-pT0
- Pro-Q20
- DW

Different MPI models have different shapes

Pythia 6.421

PS, **fermilab-conf-07-706-t, in** arXiv:0803.0678 [hep-ph]

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F^2 \rangle - \langle n_F \rangle^2}$$

Sjostrand, van Zijl, PRD36:2019,1987

Summary

- The Low-Energy LHC runs offer a unique possibility to settle important business

- These are questions faced by every person (within or outside experiments) trying to constrain ('tune') physics models

- In a broader context, they concern our *knowledge* of nature
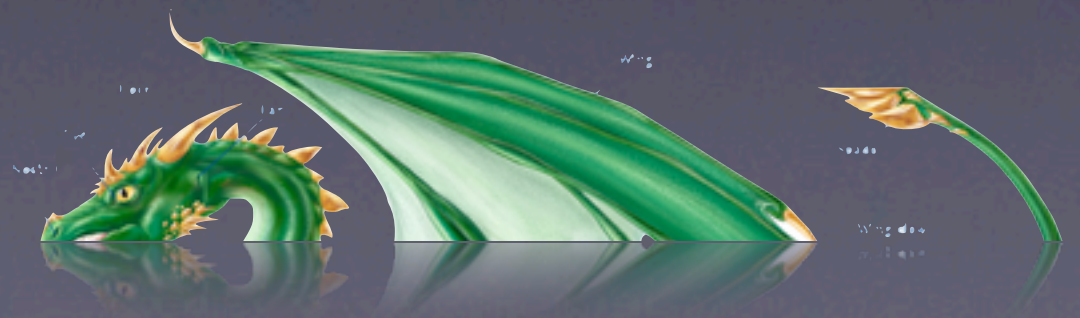
A Systematic Dissection

Perturbative Dynamics :
Infrared **safe**
observables   "pQCD"
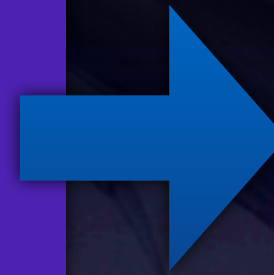
Single-Jet Spectra
Jet-Jet distributions
IR safe Energy Flow variables

Non-perturbative dynamics :
Infrared **sensitive**
observables   "MB"

Single-Particle Spectra
Particle-Particle distributions
Quantum Number Flow variables

A Systematic Dissection

Perturbative Dynamics :
Infrared **safe**
observables "pQCD"

Single-Jet Spectra
Jet-Jet distributions
IR safe Energy Flow variables

"UE"

IR-sensitive vs IR-safe
observables
(e.g., $\langle Nch \rangle$ vs pTjet)

Non-perturbative dynamics :
Infrared **sensitive**
observables "MB"

Single-Particle Spectra
Particle-Particle distributions
Quantum Number Flow variables

Modeling Diffraction

- PYTHIA 6

- POMPYT, POMWIG

- PHOJET (& Relatives)

- PYTHIA 8

- HERWIG++

- SHERPA

- EPOS, RAPGAP, ...

PHOJET (& Relatives)

(1) Cut Pomeron (1982)

- Pomeron predates QCD; nowadays $\sim$ glueball tower
- Optical theorem relates σ_{total} and σ_{elastic}
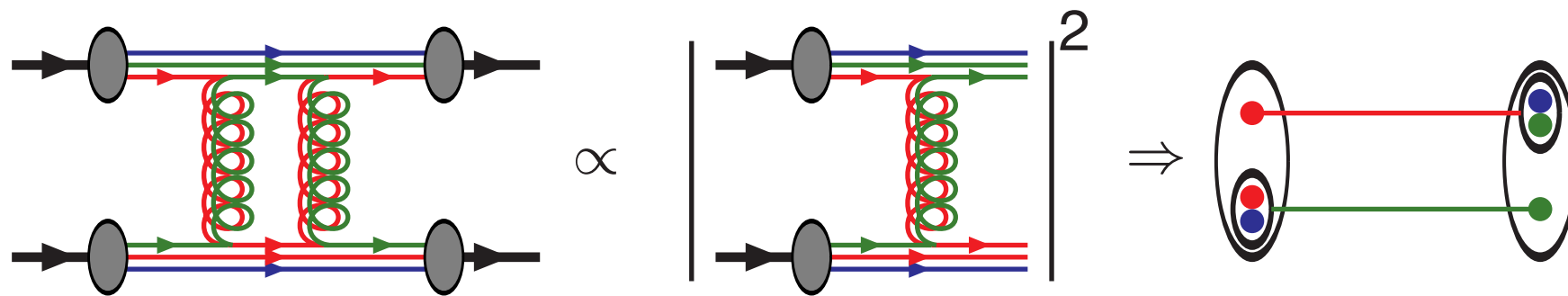
- Unified framework of nondiffractive and diffractive interactions
- Purely low-$p_\perp$: only primordial $k_\perp$ fluctuations
- Usually simple Gaussian matter distribution

(2) Extension to large $p_\perp$ (1990)

- distinguish soft and hard Pomerons (cf. Ivan):

  soft = nonperturbative, low-$p_\perp$, as above

  hard = perturbative, "high"-$p_\perp$
- hard based on PYTHIA code, with lower cutoff in $p_\perp$

Status: PHOJET web site to be resurrected soon
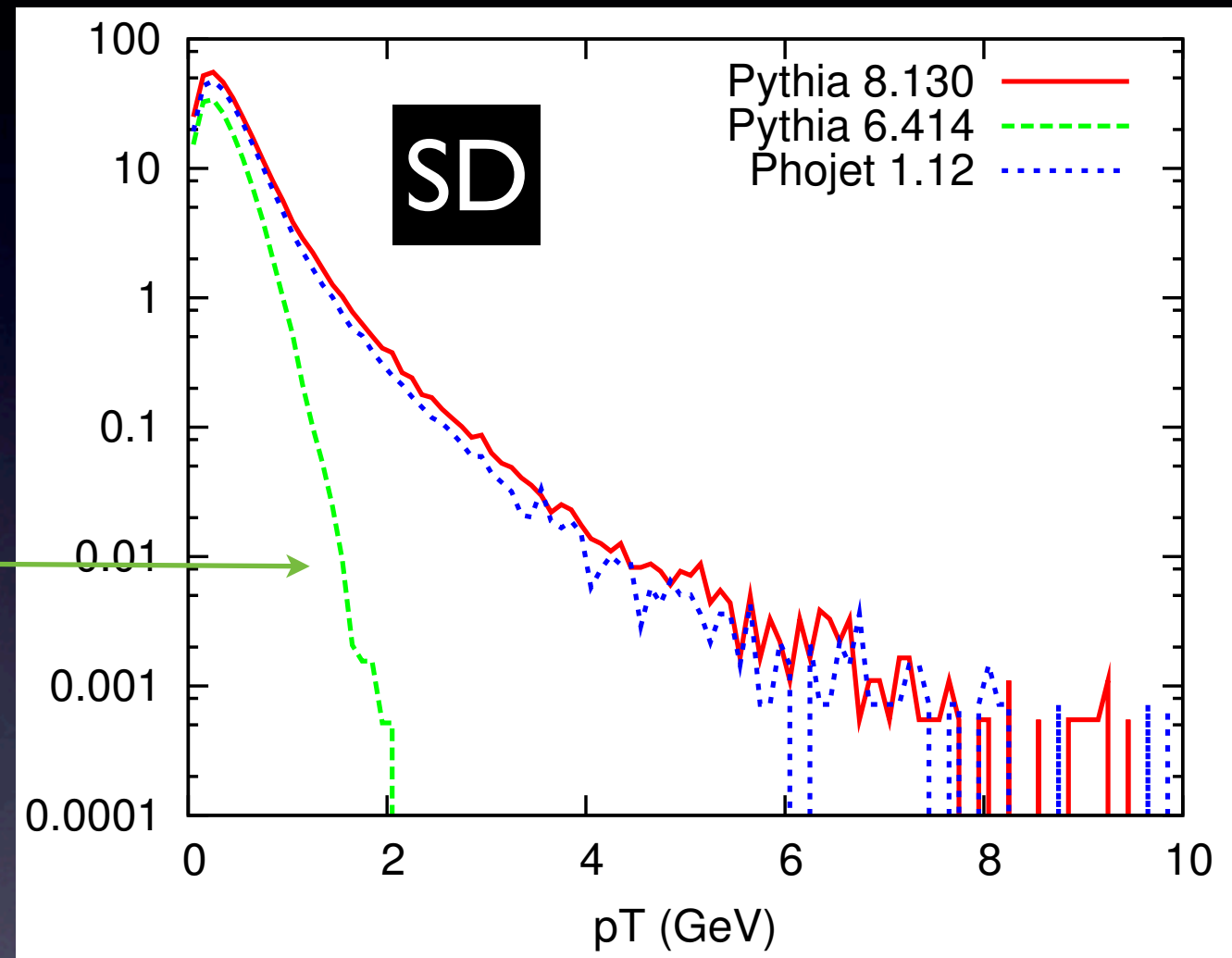
PYTHIA 6

Diffractive Cross Section Formulæ:

$$\frac{d\sigma_{sd(AX)}(s)}{dt\,dM^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{sd(AX)}t)\,F_{sd}\,,$$

$$\frac{d\sigma_{dd}(s)}{dt\,dM_1^2\,dM_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{dd}t)\,F_{dd}\,.$$

Spectra:

2 m_{pi} < M_D < 1 GeV: 2-body decay

M_D > 1 GeV : string fragmentation

Partonic Substructure in Pomeron:

Only in POMPYT addon (P. Bruni, A. Edin, G. Ingelman) ▶ high-p_T "jetty" diffraction absent

Very soft spectra without POMPYT

Status: Supported, but not actively developed

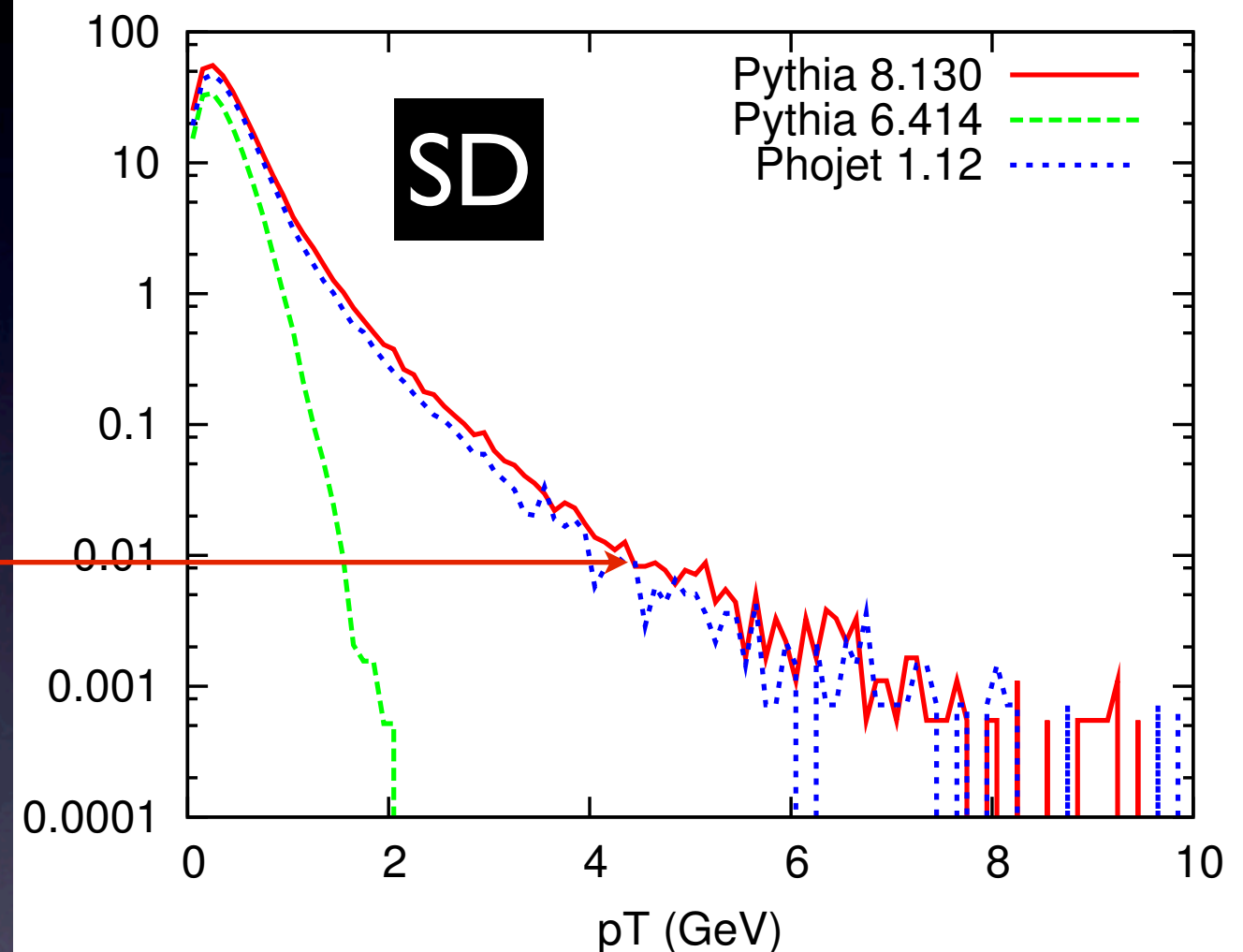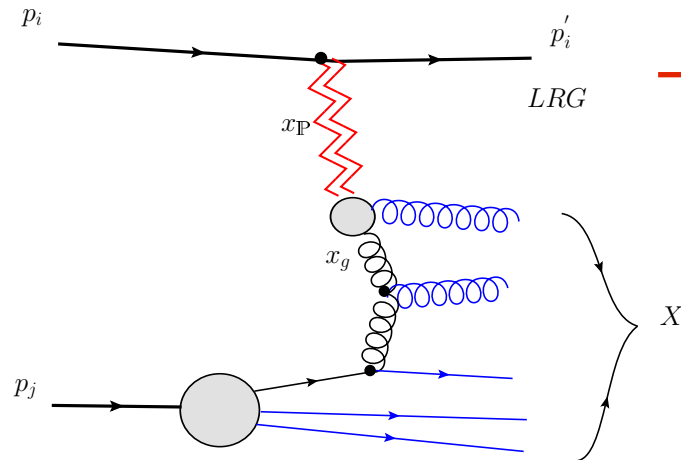# PYTHIA 8

S. Navin (MCnet) + T. Sjöstrand

Diffractive Cross Section Formulæ:

$$\frac{\mathrm{d}\sigma_{\mathrm{sd}(AX)}(s)}{\mathrm{d}t\,\mathrm{d}M^2} = \frac{g_{3\mathbb{P}}}{16\pi}\,\beta_{A\mathbb{P}}^2\,\beta_{B\mathbb{P}}\,\frac{1}{M^2}\,\exp(B_{\mathrm{sd}(AX)}t)\,F_{\mathrm{sd}}\ ,$$

$$\frac{\mathrm{d}\sigma_{\mathrm{dd}}(s)}{\mathrm{d}t\,\mathrm{d}M_1^2\,\mathrm{d}M_2^2} = \frac{g_{3\mathbb{P}}^2}{16\pi}\,\beta_{A\mathbb{P}}\,\beta_{B\mathbb{P}}\,\frac{1}{M_1^2}\,\frac{1}{M_2^2}\,\exp(B_{\mathrm{dd}}t)\,F_{\mathrm{dd}}\ .$$

Partonic Substructure in Pomeron:

Follows the approach of Pompyt

- ▶ $M_X \leq 10\,\mathrm{GeV}$: original longitudinal string description used
- ▶ $M_X > 10\,\mathrm{GeV}$: new perturbative description used
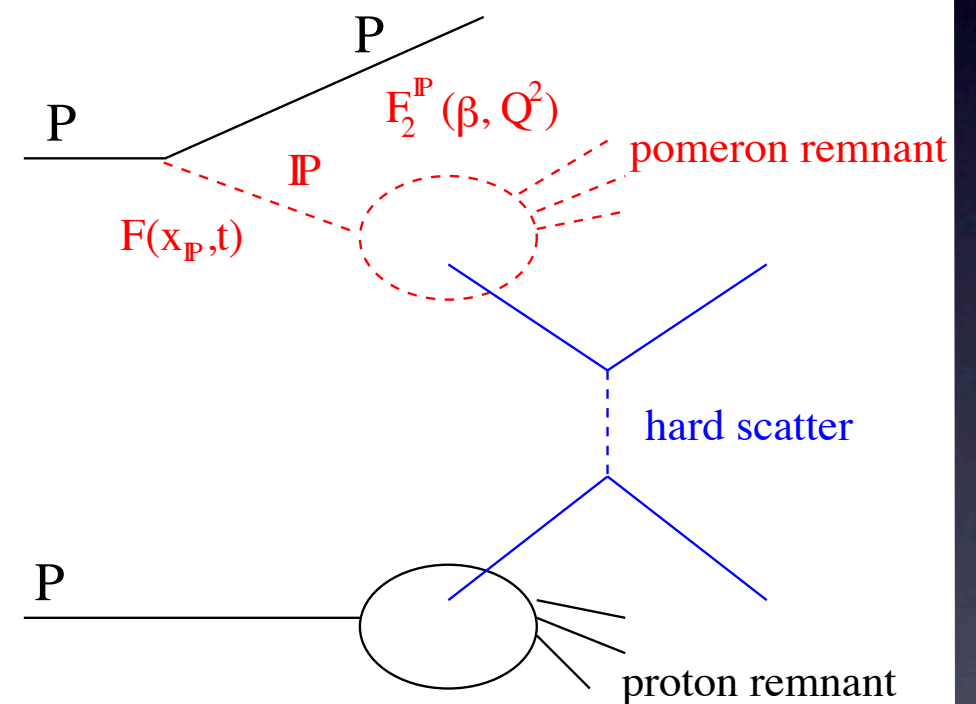
Status: Supported and actively developed

POMWIG & POMPYT

- Add-ons to F77 HERWIG and PYTHIA to include Pomeron structure

- POMWIG with DPEMC also includes central, e.g., $\mathbb{P}\mathbb{P}$>H

POMPYT: http://www3.tsl.uu.se/thep/MC/pompyt/
POMWIG: B. Cox, J. Forshaw, CPC144(2002)104
DPEMC: M. Boonekamp, T. Kucs CPC167(2005)217

POMWIG Status: Stable, migrating to HERWIG++

Current Status

- PYTHIA 6

  Obsolete

- POMPYT, POMWIG

  Stable

- PHOJET (& Relatives)

  Resurrected

- PYTHIA 8 (POMPYT-based)

  S. Navin Active

- HERWIG++ (POMWIG++)

  P. Ruzicka R&D   MCnet

- SHERPA (KMR)

  K. Zapp R&D

- EPOS, RAPGAP, ...

  ?